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DESIGN GUIDE: DESIGNING AND BUILDING HIGH VOLTAGE POWER SUPPLIES

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This report contains an accumulation of publications and analyses aimed at developing guidelines for improving both high voltage and low voltage power supplies for the U.S. Air Force systems command. It is the intent of the report to supply good design and manufacturing techniques for the packaging and the building of high quality, reliable, long-life power supplies. These data are based on the wealth of engineering practices established by design and manufacturing engineers.

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FOREWORD

This Interim Technical Report covers the work performed on contract Nos. F 3360187 M 7499 through F 3360187 M 8081, project 2418, entitled, "High Voltage Power Supply Design and Reliability Handbook," for the period 20 July 1987 through 19 July 1988.

This contract was performed by the Space Power Institute, Auburn University, Auburn, Alabama 36849 for the U.S. Air Force Materials Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433. The Program was under the technical direction of Dr. Bill Dobbs, AFWAL/MLSA with assistance from Mrs. Lavera Floyd and Mr. John Price of ASD/ENA. The Program Manager for Auburn University was Dr. M. Frank Rose. Other key personnel were William G. Dunbar, Research Associate, Space Power Institute and Lt. Chris Tarvin, AFWAL/MLSS.

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SECTION I
INTRODUCTION

There are several different types of power supplies in common use. Typical are constant voltage dc, ac-to-dc linears, ac-to-dc switches, and dc-to-dc converters. There are also distinct power ranges for power supplies. By way of definition, low power is assumed to be ac-to-dc power supplies under 300 W and dc-to-dc converters up to 50 kW. At present, only a few applications have power levels greater than 50 kW, but as technology advances more equipment designers will be assigned to develop very high power units.

The trend in military avionic systems has always been for highest performance with the most capability in the smallest possible package. Almost all early power supply designers, including those designing very high power units, were forced to increase the magnetics frequency upward to 20 kHz. Current operating frequencies in the 50 to 250 kHz range are common, with future trends indicating operating frequencies of 1 MHz. This will require advanced component technology, a better understanding of materials and processes, and judicious applications of advanced design principles. Unfortunately, in many present designs the need for high frequency has pushed the size of the signal processing and conditioning units to their maximum leaving a very small area for power conditioning electronics. As a result, the power density must increase, which, in turn, affects the heat transfer requirements, and makes electromagnetic compatibility issues more complex.

Many power supply buyers have procured this new high technology equipment, which seemed to work based on qualification testing, only to find out later that the test margins were insufficient to meet manufacturing tolerances. Thus, many units failed to achieve the high reliability anticipated. By specifying acceptable electrical characteristics, many field failures with the attendant cost and dissatisfaction will be eliminated.

The objective of the handbook is to present design, component selection, packaging, manufacturing, and test material data for engineers and technicians in the areas relevant to electronic power supply design. It is hoped this handbook will enhance the designer's capability to design, develop, and manufacture long-life, reliable, cost-effective power supplies for the U.S. Air Force. The data are aimed primarily at high voltage equipment, but a power supply seldom exists without a low voltage input and, in most cases, one may have low voltage output. Thus, data for low voltage power supplies are included in this document. To develop these data, the contents of several technical publications have been reviewed and the best of each was used in this handbook. We have chosen data that each author found useful in his design field. The actual electrical and electronic designs of equipment are not developed because many design handbooks and computer programs are available for that purpose. Since most U.S. Air Force power supplies must be built to supply a specific load characteristic, a multitude of terrestrial and electronic designs would be required to cover all applications. Only ground support and electrical equipment can really afford a truly "common" power supply consistent with space, weight, form, fit, and function that are specified to meet load demands.

The need for advancement and technology transfer in the standardization, failure analysis, and repair of power supplies has been requested by PRAM and Air Logistic Center (ALC) offices for several years. Government and industrial review teams have met, formed committees, reviewed problem areas, and developed many solutions to the problem. In each case, one very important component has been omitted, i.e. personnel. For over 25 years, high voltage workshops have been held by Government and technical societies. At these meetings the same problems appear year after year, and about every 10 years, it has been observed that the same mistakes and problems reappear by the new scientists and engineers entering the field of power supply design. It is hoped that this handbook will provide some useful data for those entering the field as they develop electronics power supplies for the U.S. Air Force Systems Command.

SECTION II
BACKGROUND

2.1 Historical Perspective. High voltage has been used for electrical power system generation, transmission, and distribution for over 75 years. Likewise, electronic manufacturers have been designing X-rays and radio and television transmitters and receivers for many years with excellent success.

High voltage techniques began to be applied to military equipment during World War II with the advent of high-power communications and radar for airplanes. This technology has continued and formed the basis for applications in space. About 20 years ago, high voltage components were built for selected spacecraft systems where specific requirements for performance could be achieved in no other way.

There are basic differences between terrestrial/commercial, and aerospace equipment. First, the aerospace environment extends from the earth's surface to deep space: from atmospheric pressure to a hard vacuum. Second, constraints placed on the user vehicle differ enormously. Factors such as atmospheric pressure, temperature, lifting capability, electronic performance requirements, volume, and weight must be considered for acceptable design. Early sophisticated airplanes required transmitters, receivers, controls, displays, and, in the case of military vehicles, additional special electronics. Addition of these electronic devices has increased the electrical power demand from a few watts for early aircraft to well over 1 MW for special applications. Thus, an obvious need exists for compact packaging to reduce weight and volume greater than that required for airplanes. Spacecraft must maintain complete electrical system integrity while completing missions that vary from months to years.

2.1.1 Aircraft. Problems like brush wear were solved during and following World War II by developing dc generator brushes with additives and later by developing 400-Hz power systems to replace the dc generators. By using brushless 400-Hz generators, significant weight and volume savings could be

achieved. These systems are still in use on most commercial and military airplanes.

Early airplane electronic systems developed during and following World War II used either low voltage, oil-filled, or gas-filled high voltage units. Today, many of these units are encapsulated to avoid high voltage breakdown.

Encapsulation processes had to be greatly improved to meet the demands for high voltage, especially for equipment with voltages exceeding 5 kV and output power levels greater than 100 W. This equipment had to be designed to eliminate overstressing of the electrode configurations and the insulation media. The insulation techniques employed were usually a combination of encapsulants, gas, and/or liquids.

2.1.2 <u>Electrical Stress.</u> There are many ways to calculate electric field stress. Each analyst/designer has his own favorite method; however, a few basics are essential to ensure commonality of method. Commercial electrical equipment may be designed with an average field stress of 2 to 8 kV/cm (5 to 20 V/mil) within the electrical insulation. By contrast, aerospace designs specify average electric stress between 20 to 80 kV/cm (50 and 200 V/mil), which points to a need for better insulation and electrode configuration practices for aerospace applications. Both the average and maximum electrical field stress are important. Average field stress is calculated by dividing the applied voltage by the distance between electrodes. However, peak electrical stress must consider both electrode configuration and frequency. In addition to average and maximum voltage, there is a peak (transient) voltage, which the system must be designed to sustain. Each must be considered in any design. The maximum electrical field stress in any high voltage system is that stress at the electrode surface corresponding to areas with minimum radius of curvature (approaching a point). In addition, there is a voltage distribution within the circuit as a result of the transient operation. For instance, most of the voltage across an inductor during a short duration transient (less than 50 s) is impressed across the initial 15 percent of the turns of the inductor. Therefore, consideration must be given to both magnitude and distribution of the voltage transients within any packaged circuit.

A set of design guidelines has been developed using the experience of commerci l designers and experienced spacecraft high voltage equipment designers. The most important features of the design guidelines are:

- Conformal mapping of all highly stressed surfaces
- Determination of the voltage stress capability of all insulating materials used in the design
- Careful attention to details to allow design for long, trouble-free life

Packaging may be either open or closed (i.e., encapsulated). Open packaging implies that the circuits are free to come to pressure equilibrium with the outside environment. In contrast, closed circuits are encapsulated in potting materials, oils, or pressurized gases.

Oil and gas-filled designs have the advantage of operating in space much the same as on the ground, and are easily tested. Gas insulation has the disadvantage of leaking, and must have a replenishing supply. Oil insulants have the disadvantage of bubble formation. These bubbles, whose dynamics in microgravity are poorly understood, may tend to lodge within high voltage circuits (between electrodes) and cause failures. In addition, container leakage may occur. Oil from leaks can collect on optical lenses or create a fire hazard.

Encapsulation also has many problems, the worst of which is voids trapped during the potting process. This process is enhanced by the encapsulated module having surfaces of the encapsulated material exposed to the environment. Further voids and temperature cycling may cause stress cracking between high voltage electrodes and electronic parts. In addition to void problems, some materials are incompatible and will not bond to parts or circuits. All these features may lead to catastrophic failure.

There is no single preferred insulation material: one that works very well for one manufacturer may be unacceptable to another manufacturer.

The electrical parameters and quality of the encapsulant depends on the circuit, parts, cleaning, material, material processing, material handling, and application for which it is intended. As an example, silicones have good high-temperature characteristics, but are poor structurally and tend to expand.

2.2 Survey. A survey was sent to approximately 100 U.S. Air Force industrial and technical organizations having experience related to encapsulated high voltage power supplies. Their qualitative responses are discussed in this section.

The first four questions of the survey were quantitative questions oriented towards relating manufacturing defects, major material and processing factors contributing to manufacturing defects, field use reliability factors resulting from these defects, and the overall importance of key critical factors in the manufacture of encapsulated high voltage power supplies.

An analysis of the responses leads to some reasonable general conclusions. Based on analysis of the questions that deal with types of defects most common to encapsulated high voltage power supplies, the following types of defects were found to be most prevalent:

Manufacturing--

- Shorts or voltage breakdown due to cracks or microcracks in cured resin
- Corona
- Arcing and tracking
- Voids or entrapped air in cured resin
- Overheating of components during the curing process
- Separations or gas gaps formed as a result of poor adhesion of cured resin to component parts

Similarly, analysis of the responses to the second question which deals with major material and processing factors that contribute to manufacturing defects, indicates the following factors to be most common:

- Improper or uncontrolled mixing procedures
- Short working life of catalyzed resin and related resin flow problems

Materials and Processes--

- Improper or uncontrolled application of primer or substrate pretreatment
- Poor adhesion of cured resin to substrate materials
- Compatibility problems between resin, wire enamel, and/or other materials in the encapsulated assembly
- Differential thermal expansion between cured resin and other materials in the encapsulated assembly
- Poor thermal conductivity
- Complex vacuum-pressure cycles
- Operator or technician errors
- Resin shrinkage during curing
- Internal stresses in cured resin
- Improper or inadequate evacuation of air from liquid resin
- Improper or inadequate impregnation of resins into wound devices
- Complexity of process and equipment

Reliability--

- Corona
- Internal surface arcing and tracking
- Overheating of components and/or inadequate heat sinking
- Transformer failures
- Resin cracking
- Wire, cable, and connector failures
- Purchased component failures
- Both short and open circuit failures of unknown orig
- Replacement of non-foiled parts or modules

Manufacturing Factors. Critical factors in the manufacture of encapsulated high voltage power supplies indicate three important points, as follows:

a. Most respondents felt that high yield with minimum repair is desirable. In general, this emphasizes the need for high-performance ruggedized resins having low thermal expansion and high dimensional stability. All respondents rated this factor as "very important."

b. A high percentage of respondents felt that soft resins having easy repairability, or two resins to accommodate repair where mandatory, were very important. Most respondents thought adhesion, which is a problem with soft repairable resins, was a very important factor.

c. Most respondents felt that designs for control of electrical stresses were extremely important, i.e., better design could reduce manufacturing problems.

Analysis of other written responses showed a trend of comments and recommendations that are generally in line with the quantitative responses discussed previously. These responses dealt with yield, cost, and reliability. This provides the most recurring recommendations

- Design the power supply to minimize high voltage breakdown and stressing problems, separate high and low voltage areas. and educate designers
- Be sure that circuit board designs will withstand all high voltage power requirements
- Design system for maximum heat transfer
- Train personnel associated with the manufacture of high voltage power supplies
- Select highest performance materials, and allow for repairability where mandatory; ensure quality control of materials

- Consider partitioning to allow use of high-performance ruggedizing designs where possible and soft repairable resins where absolutely necessary
- Use low thermal expansion resins and fillers
- Use high adhesion resins where possible; control adhesion by highly controlled assembly cleaning and tightly controlled use of primers
- Use adequate, controlled cleaning processes; prebake all parts to be encapsulated
- Verify that parts are environmentally tested in a non-contaminating liquid or atmosphere such as silicone oil
- Screen critical components; qualify the design
- Control workmanship in critical processes, especially encapsulation and coil winding; give special attention to documentation for materials, processes, and controls
- Verify freedom from voids, cracks, contamination and other sources of high voltage breakdown
- Place special emphasis on transformers, because they are usually dedicated devices for each system. Specific transformer construction details are highly critical
- Control fabrication equipment performance

General summary comments from a comprehensive literature survey are consistent with the results of our more specific survey. They are summarized as follows:

- Critical pressures often exist in equipment at space altitudes because of time delays in outgassing or for other reasons such as firing of gas control jets
- Major defects in encapsulating high voltage equipment are voids, cracking, and poor adhesion of resin to components and parts
- Primers required to achieve adhesion of silicone resins to components and parts are specific potential sources of adhesion problems

- Short pot life, high viscosity, inadequate compound evacuation and faulty pouring techniques lead to voids
- Thorough cleaning and removal of entrapped moisture are critical operations preceeding encapsulation
- Transformers are especially critical components in high voltage systems
- Design high voltage equipment to minimize electrical stresses
- Low thermal expansion and high thermal stability are desired properties for high yield and reliability

2.2.1 Survey Evaluation. The final survey information confirmed the initial premise that there are five major areas of concern: materials selection, materials handling, fabrication, field stresses, and testing. There are many subtopics under these five, such as corona, bonding, and voids.

Typical failure rates are shown in Table 1. These percentages imply that production with the lowest rate may require better inspection and test to eliminate unflightworthy equipment. As an example of a test procedure that could be applied, corona testing can detect most voids and cracks that would contribute to failure. It is a simple, easily implemented technique.

It was recognized before the questionnaire was formulated that corona and flashover/arcovers are the results of voltage stress, voids, and faulty or improper insulation. The terms corona and arcover were added because they are terms commonly used in failure reports. Therefore, it can be seen that most failures result from insulation overstress and voids. All other failures can be attributed to processing, including parts cleaning, area cleanliness, and workmanship. One response included lack of funding and time as items responsible for many problems, such as:

- Improper insulation selection
- Electrical overstress due to improper packaging design caused by rushing the design
- Workmanship
- Process control and cleanliness

TABLE 1
PARTS FAILURE OCCURRENCES

	Failure Occurrence by Program Phase (%)		
	Developmental	Production	Field Operation
Insulation	95	76	82
Control Circuits	85	81	86
Transformers	95	64	73
Regulators	91	84	75
Rectifier/Filters	95	76	77
Capacitors	86	71	71
Inductors	60	45	43

Cause of Failure: Most prevalent causes of failure are listed as follows:

Cause of Failure (27 Reports)	Percent
Inadvertant Air Voids	59
Arcover	52
Corona of Partial Discharges	52
Faulty Electronic Parts	48
High Electrical Stress Area	48
Board Delamination	4
Parts Contamination	4
Manufacturing Processes, Workmanship, Production	22
Human Error	4
Improper Handling by User	4
Funding and Time	4
Design Problems	4

A few manufacturers and users do not require environmental and burn-in testing. This is surprising because these tests are usually required to determine the quality of assemblies. For very high quality assemblies, environmental and burn-in tests are performed on circuits and parts before final assembly. These companies, which perform additional tests to determine product reliability list as follows:

- Corona, 63 percent
- Dielectric withstanding voltage (DWV), 33 percent
- Life, 37 percent

Although these additional tests are expensive, the partial discharge (corona) test is one of the quickest methods for determining cracks and voids in insulation. The DWV test is a proven test for long-life commercial equipment and should be used for aircraft electronic components and systems, provided there is no danger of circuit or component damage from the application of high voltage to the system.

Most manufacturers used vacuum impregnation or pressure molding of potting materials. These should be considered as standard practice. The remainder used vacuum potting with subsequent overpressure. This latter method is most desirable for voltages greater than 10 kV and limits voids to less than 1.0 mil diameter. Other methods reported are:

- Trickle potting, 22 percent
- Casting (pressure), 37 percent
- Transfer molding, 11 percent

Fifty percent of the manufacturers also pot the low voltage circuits. Potting the low voltage circuits in place occasionally is done simply to hold meshed parts in an exact configuration. However, the high frequencies associated with partial discharges can be conducted through the high dielectric constant potting material to critical parts in the low voltage

circuitry and cause circuit damage. The other 50 percent used conformally coated circuit cards for low voltage circuits.

The following military standards and specifications are those most frequently referred to by manufacturers and users of high voltage power supplies:

- MIL-STD-454
- MIL-STD-704
- MIL-STD-810
- MIL-STD-1541
- MIL-E-5400
- MIL-E-16400
- MIL-T-27

2.3 Conclusions. It can be concluded from this industry survey that high voltage power supply failures are due to four items: packaging (high electrical stresses), design (selection of parts or improper use of parts), materials, and processes (corona, voids, diodes, workmanship, and handling). Table 2 lists the percentage of failures attributable to each of these factors. This summary implies that most designers select good materials, but processing of the materials requires major improvement.

TABLE 2

FAILURE ANALYSIS CONCLUSIONS

ITEM	PERCENTAGE
Design	48
Packaging	48
Materials	34
Processes	81

SECTION III
FUNDAMENTALS OF INSULATION

Changes in insulation properties resulting from electric field temperature variations, mechanical stress, and surface contact with electrodes are fundamental contributors to voltage breakdown. The designer dealing with these changes in insulation properties needs to understand certain fundamental characteristics of insulation behavior. Basic theory of gas, liquid, and solid insulation is provided in this section, and excellent texts on dielectric phenomena are also available (References 1 through 5).

3.1 Gases. Much has been written about gaseous breakdown theory. Data obtained under a variety of test and analytical conditions have been published in the literature (References 6 through 16). A brief review and discussion of this theory follows.

3.1.1 Theory of Gas Breakdown. When an electrical potential is impressed across a gas, a small prebreakdown current can be measured. It is caused by free electrons and ions generated by background radiation from radioactive materials or cosmic rays. At low potential the electrons and ions drift through the gas and collide with neutral gas molecules when subjected to an electric field. As the potential is raised, the energy gained by the electrons and ions between collisions increases. Ions share their energy with the neutral molecules in collisions but the electrons can accumulate energy over several collisions and gain enough energy to excite and ionize neutral gas molecules, resulting in new ion pairs. The resultant new free electrons are accelerated and, by colliding they ionize more molecules, generating electrons at an exponential rate with respect to the applied voltage. This process is called avalanche breakdown of the gas (References 6 through 16). A typical voltage current characteristic is shown in Figure 1. If there are no initiating electrons, then for a uniform field (parallel plate) gap with electrode separation d, the number of electrons (N) reaching the anode is

$$N = N_0 e^{\alpha d}$$

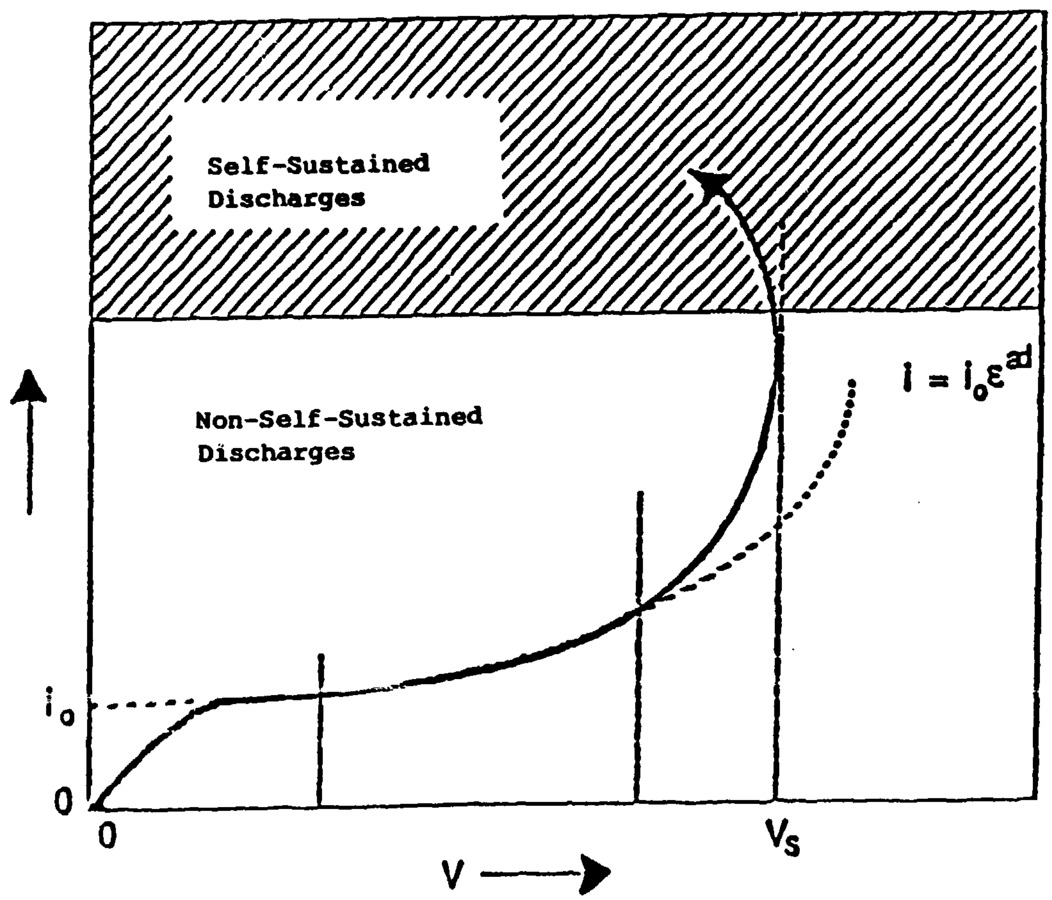


Figure 1. Voltage-Current Characteristic Function for Ionization and Breakdown in a Uniform Field Gas Gap

where α is the first Townsend ionization coefficient, defined as the number of ionizations per centimeter path length in the field direction.

Further increase in applied voltage puts us in the breakdown region where additional electrons are released principally by positive ions, ultraviolet emission or metastable molecules produced in the avalanche. Townsend's criterion for breakdown is

$$\gamma(e^{\alpha\delta}-1) = 1$$

where γ is the second Townsend coefficient, defined as the number of secondary electrons emitted per electron in the path.

Electronegative gases have molecules with other energy levels (rings) deficient in one or two electrons, which are capable of capturing free electrons, and forming negative ions. These gases have high dielectric strength because of their ability to attach electrons and remove them from the breakdown process. The number of attaching collisions made by one electron drifting 1 cm in a field is the attachment coefficient n and d is the path length. The criterion for breakdown in an electronegative gas is:

$$\frac{\gamma\alpha}{\alpha-n}\left[e^{\alpha d} - 1\right] = 1$$

Gases with oxygen and halogen atoms are electronegative and hence good insulators, in contrast to hydrocarbon and noble gases. Some electronegative gases are sulfur hexaflouride (SF_6) dichlorodifluoromethane ($CCl_2\ F_2$), perfluoropropane ($C_3\ F_8$), perfluorobutane ($C_4\ F_{10}$), hexafluoroethene (C_2F_6), chloropentafluoroethene ($C_2Cl_2F_5$), dichlorotetrafluoroethane ($C_2Cl_2\ F_4$), tetrafluoromethane (CF_4), and nitrogen or fluorocarbon mixtures.

3.1.1.1 Paschen Law. The breakdown voltage of a uniform-field gap in a gas can be plotted to relate the voltage to the product of the gas pressure times the gap length. This in known as Paschen's law curve (References 6 through 8). The law may be written in the general form:

$$v = f(\rho d)$$

where ρ is the gas density, and d is the distance between parallel plates. Paschen's law states: "As gas density is increased from standard temperature and pressure, the voltage breakdown is increased because at higher densities the molecules are packed closer, and a higher electric field is required to accelerate the electrons to ionizing energy within the mean free path. The voltage breakdown decreases as gas density is decreased from standard pressure and temperature because the longer mean free path permits the electrons to gain more energy prior to collision. As density is further decreased, the voltage breakdown decreases until a minimum is reached."

As density is further reduced to values less than the Paschen law minimum, the voltage breakdown rises steeply because the spacing between gas molecules becomes so large that, although every electron collision produces ionization, it is hard to achieve enough ionizations to sustain the chain reaction. Finally, the pressure becomes so low that the average electron travels from one electrode to the other without colliding with a molecule. This is why the minimum breakdown voltage varies with gas density and spacing. Examples of Paschen-law curves for several gases are shown in Figure 2.

The pressure corresponding to minimum breakdown depends on the spacing of the electrodes. For a 1 cm spacing at room temperature this pressure occurs at 100 to 300 Pa depending on the gas used in the experiment. One Pa is equal to 1 N/m^2 or 7.5×10^{-3} torr. A representative minimum for air is 326 volts dc. For an electrode spacing of 1 cm at standard atmospheric conditions the breakdown voltage of air is 31 kV. The Paschen law is valid except at higher pressures where the pressure P_1 is no longer simply proportional to P_2, e.g., at several atmospheres in SF_6 (Reference 17) where P_1 is the sea level pressure and P_2 is the test gas pressure.

When the pressure is increased to values greater than two atmospheres, or when the field exceeds approximately 100 to 200 kV/cm, Paschen's law is no longer satisfied. The breakdown voltage is lower than predicted (Figure 3)

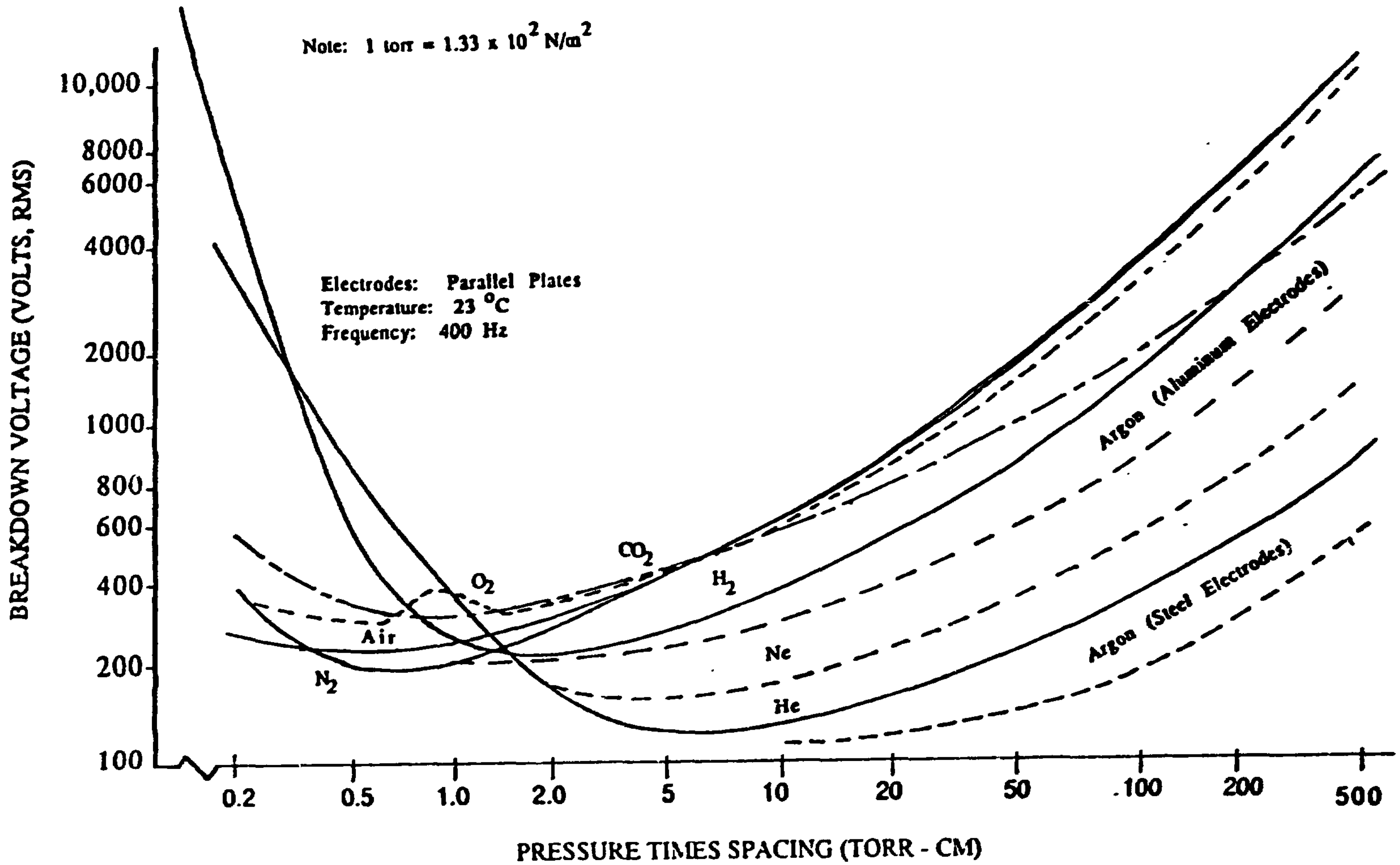


Figure 2. Voltage Breakdown of Pure Gases as a Function of Pressure Times Spacing

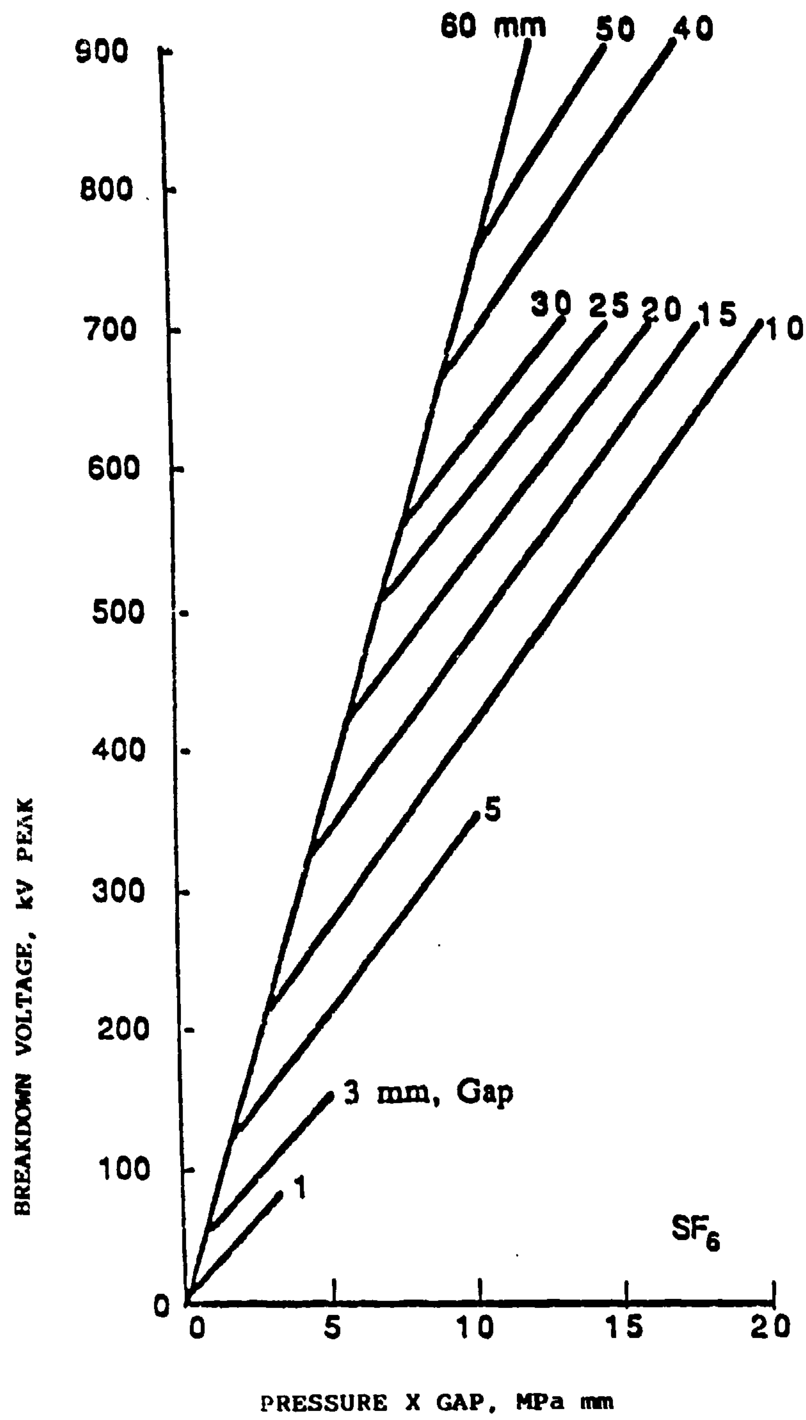


Figure 3. Paschen Plot for AC Uniform Field Breakdown in Clean SF_6

(Ref. 18). Also, with increasing pressure, the breakdown voltage tends to reach a maximum or saturate (Reference 6, 17, and 18). These effects are due to electrode surface roughness causing enhanced ionization at microscopic surface projections (Reference 17). In this region there is also an "area effect" where the breakdown strength decreases with increasing area. This can be mathematically treated by extreme value statistics (References 17 and 19), and is related to the number of defects per unit area.

3.1.1.2 Penning Effect. Penning (Reference 13) discovered that if a trace (much less than 1 percent) of a gas such as argon is mixed into a gas such as neon, a large reduction in the breakdown voltage occurs. This is caused by the metastable neon atoms ionizing the argon atoms. Gas mixtures having this characteristic are helium-argon, neon-argon, helium-mercury, and argon-iodine. Airplane compartments containing helium must be kept free of argon to prevent the possibility of low voltage breakdown.

3.1.1.3 Breakdown Strength of Gases. Electrical and electronic equipment must be designed to operate at the maximum specified altitude and temperature. Table 3 lists the potentials required for voltage breakdown in gases at the minimum pressure-spacing condition (Paschen-law minimum) and between parallel plates spaced 1 cm apart at pressure. Of these gases, conditioned air is used whenever possible. It is not recommended to use some gases at low pressure because they may give off toxic fumes or form a corrosive decomposition product; therefore many high voltage modules are either potted or pressurized.

3.1.2 Pressurizing Gases. Pressuring gases include all the gases listed in Table 3 and shown in Figure 3. Some gases have very low breakdown characteristics and should not be considered. Helium is an example. Fluorocarbons are the preferred gases. Of these gases, sulfur hexafluoride is generally the preferred gas because it is stable, electronegative, and easily contained. Sulfur hexafluoride (SF_6) gas is used in compact switching equipment, substations, cables, and other commercial high voltage equipment. It should be the first gas considered for high voltage airplane equipment when component high density packaging and other high voltage criteria suggest that a gas-pressurized installation is best.

TABLE 3

BREAKDOWN VOLTAGE BETWEEN BARE ELECTRODES SPACED ONE CENTIMETER

Gas	Minimum at Critical Pressure Spacing		Breakdown Voltage at 1 Atmosphere	
	Volts (a.c. rms)	Volts (d.c.)	Kilovolts (a.c.)	Kilovolts (d.c.)
Air	223-230	315	23	33
Ammonia	---	---	18.5	26
Argon	196	280	3.4	4.8
Carbon Dioxide	305	430	24	28
Freon 14	340	480	22.8	32
Freon 114	295	420	64	90
Freon 115	305	430	64	90
Freon 116	355	500	--	--
Freon C 138	320	450	--	--
Helium	132	189	1.3	1.63
Hydrogen	205	292	12	17
Nitrogen	187	265	22.8	32
Oxygen	310	440	--	--
Sulfur Hexafluoride	365	520	63	89

Electronegative gases are chemically inert and have good thermal stability, but can decompose chemically when exposed to partial discharges or arcs. The products of decomposition are often toxic and corrosive. In addition, a small quantity of water decomposes the SF_6 to form hydrofluoric acid when in the presence of a partial discharge or arc. Once formed, the hydrofluoric acid etches into crevices and requires special cleaning of all parts within the pressurized module. Examples for the breakdown-voltage equations for SF_6 are shown in Tables 4 and 5. The equations are based on measurements made primarily using coaxial-cylinder gaps.

Figure 4 shows dc and ac Paschen curves for SF_6 in uniform fields, and data are presented in Table 6 (Reference 20). The minimum of the Paschen curve occurs at 35 Pa-cm and is near 500 volts dc. Deviations exist for values above 300 kPa-cm and below 10 Pa-cm for small spacings and high pressures. A comparison of the voltage breakdown of SF_6, N_2, and other gases is shown in Figure 5. Air, if used, must be very dry.

SF_6 gas has excellent heat transfer and dielectric properties, making it an excellent pressurizing gas. Mixing SF_6 with other gases will improve some characteristics with little change to the direct voltage uniform field dielectric strength, as shown for mixtures in air, carbon dioxide, and nitrogen in Figure 6 (Reference 21).

Dielectric coated electrodes can increase the voltage breakdown in gases compared with bare electrodes as shown in Figures 7 and 8 for polyurethane coated and anodized-aluminum electrodes for the gas pressures and thicknesses indicated (Reference 22). This technique for increasing breakdown voltage is not recommended unless the coating materials are given sufficient life testing and the coating process is held to a very tight tolerance. The use of coatings applied to electrodes can be recommended for improving safety margins; however, a coating that becomes unbonded will flake or blister, lowering the breakdown voltage to levels less than those for base electrodes materials.

TABLE 4

SPARKOVER GRADIENTS IN AIR

Pressure $N/m^2 \times 10^5$	Electrode Geometry (See Fig. 6)	Range of Dimension mm (See Fig. 6)	Voltage Waveform	Equation E_s in kV/mm	Typical Error Range
1.013	concentric cylinders	$0.59 \le r_1 \le 15.9$ r_2 not specified	50 Hz (3.1)	$E_s = 3.1(1+0.975/\sqrt{r_1})$	+ 1.4 - 5.4
1.013	concentric cylinders	$3.96 \le r_1 \le 38.1$ $r_2 = 290.5$	50 Hz (3.2)	$E_s = 2.2(1+1.71/\sqrt[3]{r_1})$	
1.013	concentric cylinders	not specified	50 Hz (3.3)	$E_s = 2.4\ 1+1.49/(r_1)^{0.4}$	
1.013	concentric cylinders		50 Hz (3.4)	$E_s^2 - 4.56E_s \ln(4.39E_s) = 5.2 + 0.24/r_1$	
1.013	concentric cylinders	$10 \le r_1 \le 150$ r_2 not specified	50 Hz (3.5)	$E_s = 2.721(1+1.55/\sqrt{r_1})$	$\pm$ 3.5
	eccentric cylinders	$12.7 \le r_1 \le 38.1$ $r_2 = 63.5$ $5 \le S \le (r_2 - r_1)$			$\pm$ 3
1 < P < 5	concentric cylinders	$25.4 \le r_1 \le 80$ r_2 not specified	50 Hz (3.6)	$E_s = 2.12(1+3.55/\sqrt{pr\ 1\times10^{-5}}$	$\pm$ 4
1.013	concentric sphere/ hemisphere	$5 \le r_1 \le 125$ $72.5 \le r_2 \le 203.2$	50 Hz (3.7)	$E_s = 2.4(1+3.16/\sqrt{r_1})$	$\pm$ 4
	eccentric sphere/ hemisphere	$8.75 \le r_1 \le 38.1$ $r_2 = 72.5$ $0 \le S \le 0.9(r_2 - r_1)$			
1.013	parallel external cylinders	$r_1 = r_2$ $0.098 \le r_1 \le 4.64$	50 Hz (3.8)	$E_s = 2.98(1+0.95/\sqrt{r_1})$	+ 3.7 - 6.2

TABLE 5

EQUATIONS FOR SPARKOVER GRADIENTS IN SF_6

Pressure 10^5 Pa	Electrode Geometry (see Fig. 6)	Range of Dimensions mm (see Fig. 6)	Voltage Waveform		Equation E_s KV/mm See note
$1 < p < 4$	concentric cylinders	$2.5 \le r_1 \le 25$ $30 \le r_2 \le 140$	50 Hz	(3.9)	$E_S = \frac{5.3(1+0.459p)}{1+(2.82-2.29/p)/\sqrt{r_1}}$
$1 < p < 4$	concentric cylinders	$19 \le r_1 \le 100$ $100 \le r_2 \le 270$	50 Hz	(3.10)	$E_S = 4.28p+3.8$
			negative impulse	(3.11)	$E_S = 6.43p+3.0$
			negative impulse	(3.12)	$E_S = 4.59p+3.5$
	sphere/sphere	$r_1 = r_2 = 125$ $20 \le g \le 80$	50 Hz	(3.13)	$E_S = 6.12p+2.3$
			negative impulse	(3.14)	$E_S = 6.74p+2.6$
$1 < p < 4$	concentric cylinders	not specified but expected to be $19 \le r_1 \le 100$ $100 \le r_2 \le 270$	positive impulse	(3.15)	$E_S = 8/12p+1.0$
$1 < p < 6$	sphere/plane	$10 \le r_1 \le 25$ $20 \le g \le 500$	positive impulse	(3.16)	$E_S = 8.78p$+correction factor
$1 < p < 5$	sphere/sphere	$r_1 = r_2 = 75$ $0 \le g \le 120$	50 Hz	(3.17)	$E_S = \frac{8.78p}{(1+0.557/\sqrt{pr_1})}$
	hemispherically ended rod/rod	$r_1 = r_2$ $5 \le r_1 \le 15$ $0 \le g \le 200$			

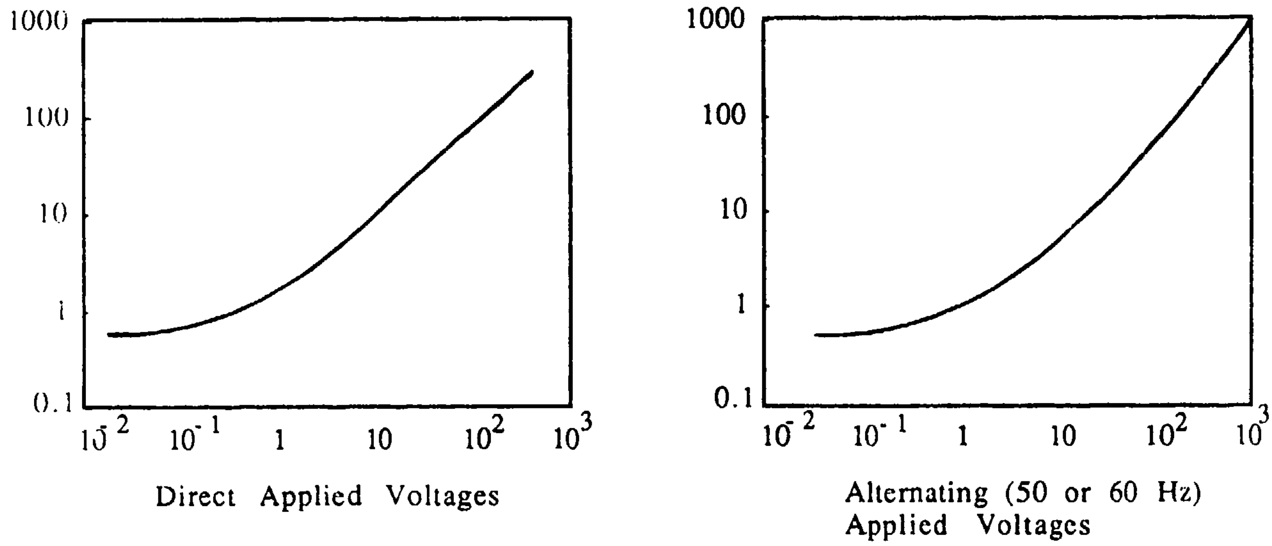


Figure 4. Paschen Curves for SF_6 with Direct and Alternating Applied Voltages

TABLE 6

AC BREAKDOWN FOR SF_6

IN UNIFORM FIELD GAPS

pd kPa cm	50 Hz CREST BREAKDOWN VOLTAGE kV — DISTANCE mm												
	1	2	3	5	8	10	15	20	25	30	40	50	60
10	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
40	26.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5
80	42.5	55.5	64.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5
100	50.0	60.0	74	89	89	89	89	89	89	89	89	89	89
200	98.0	103	120	150	168	170	170	170	170	170	170	170	170
300		144	155	190	217	240	253	253	253	253	253	253	253
400		177	185	220	250	275	303	310	310	310	310	310	310
500			216	248	275	305	356	385	385	385	385	385	385
600			250	278	305	340	395	440	455	455	455	455	455
800				335	370	390	450	500	535	580	580	580	580
1000				395	430	450	505	555	595	635	730	730	730
1200					485	505	562	610	650	685	750	805	870 **
1400					535	565	620	668	715	748	808	865	(920)
1600					585	618	678	725	768	(805)*	(865)	(920)	(970)
1800						680	733	(785)*	(825)	(862)	(925)	(975)	(1025)
2000						735	(790)*	(840)	(880)	(920)	(975)	(1025)	(1075)

*Numbers in brackets () are extrapolated which may give doubtful accuracy.

**Values below the break line lie outside the range for which the Paschen law holds true.

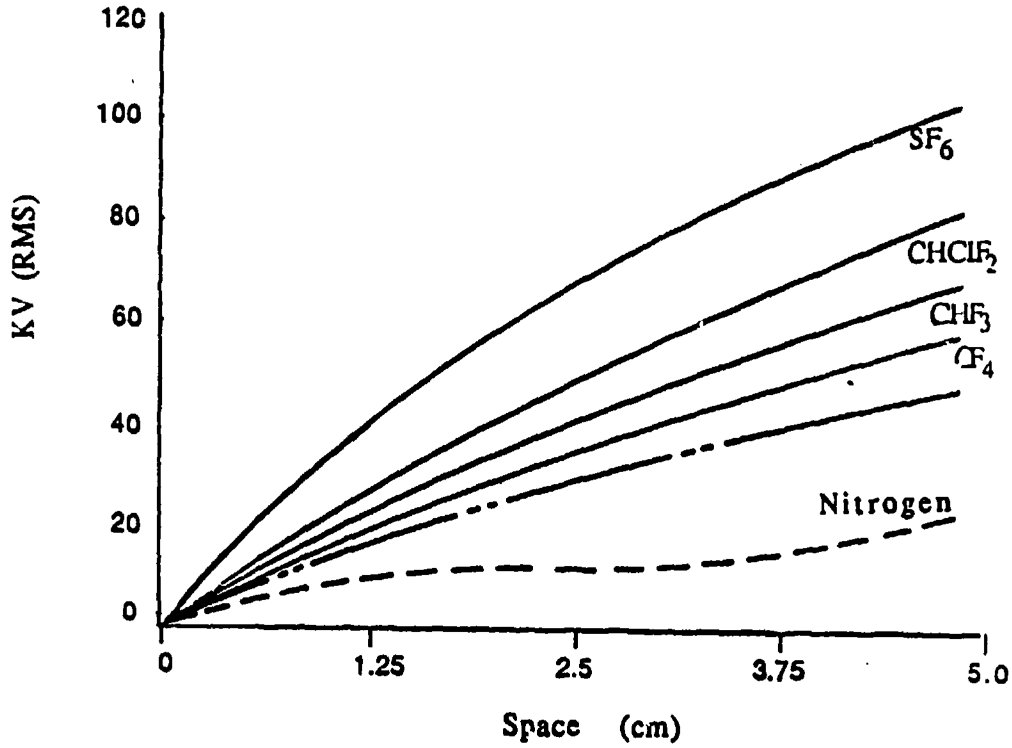


Figure 5. Breakdown Voltage Curves of Gases Between a Hemispherically-Ended Rod of 0.1 inch Diameter, and a Sphere of 1.0 inch Diameter. The Gas Pressure is 1 Atmosphere

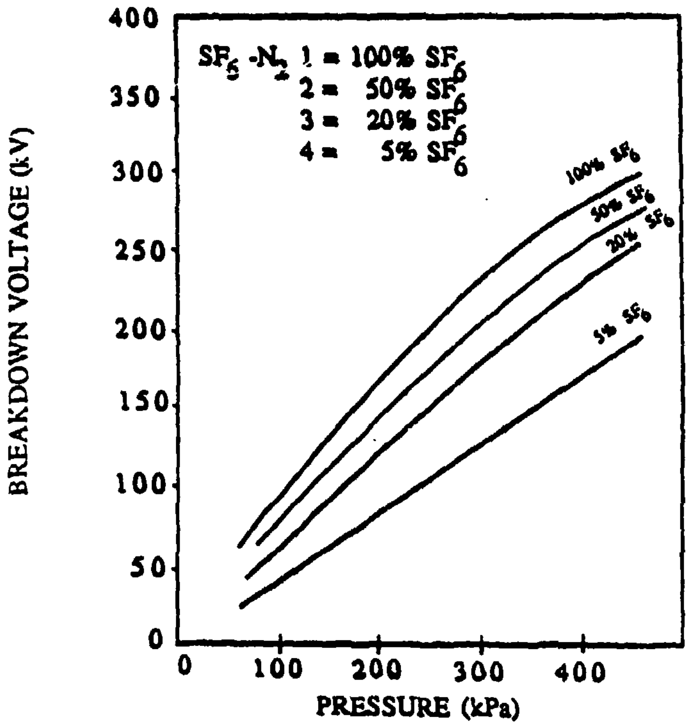


Figure 6A. Breakdown Voltages as a Function of Gas Pressure for SF_6-N_2 Mixtures

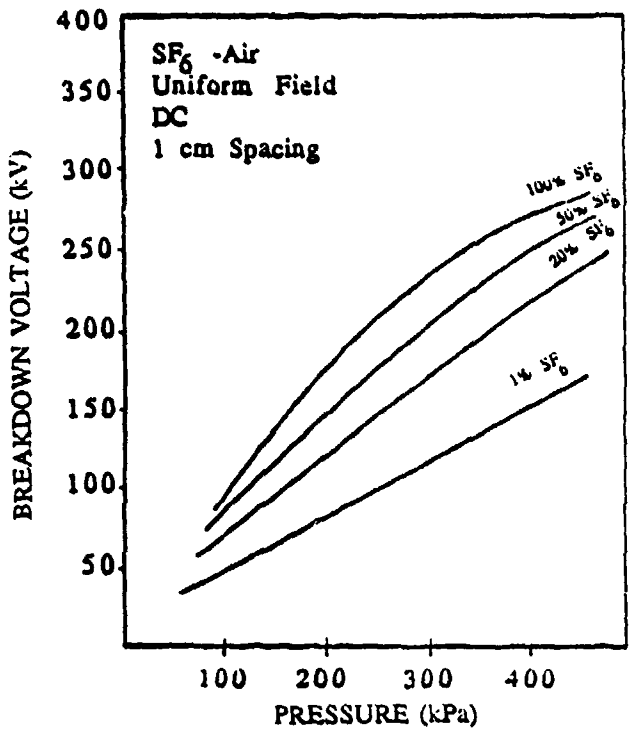


Figure 6B. Breakdown Voltages as a Function of Gas Pressure for SF_6 -Air Mixtures

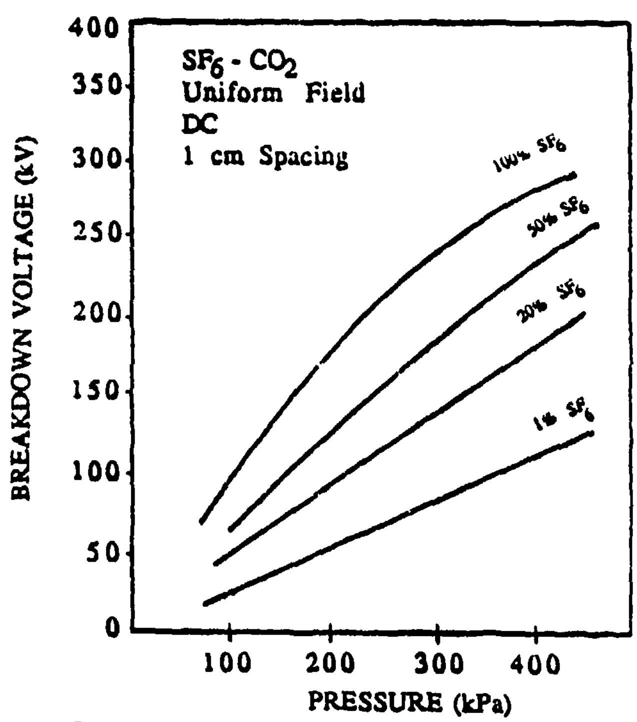


Figure 6C. Breakdown Voltages as a Function of Gas Pressure for SF_6 -CO_2 Mixtures

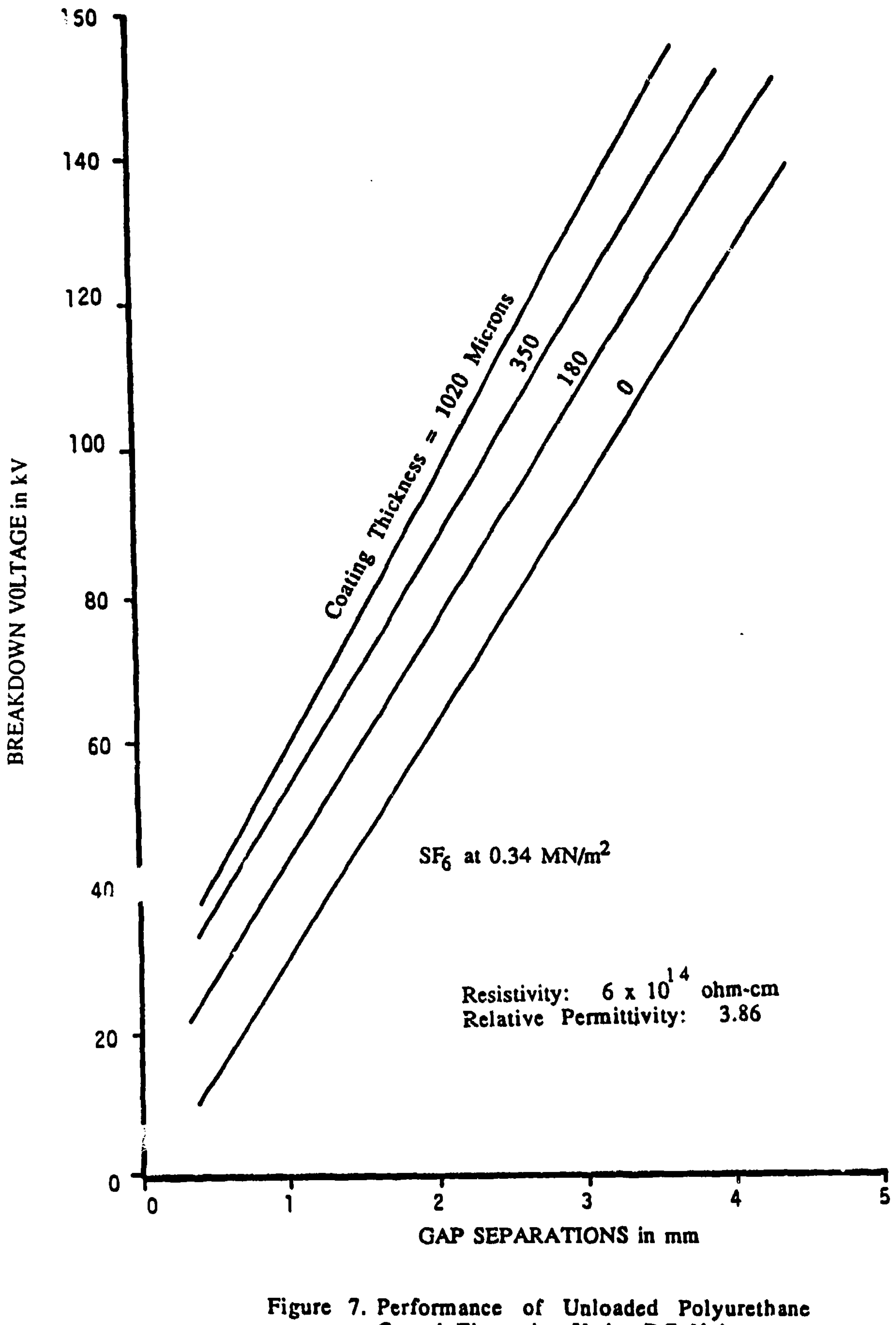


Figure 7. Performance of Unloaded Polyurethane Coated Electrodes Under DC Voltages

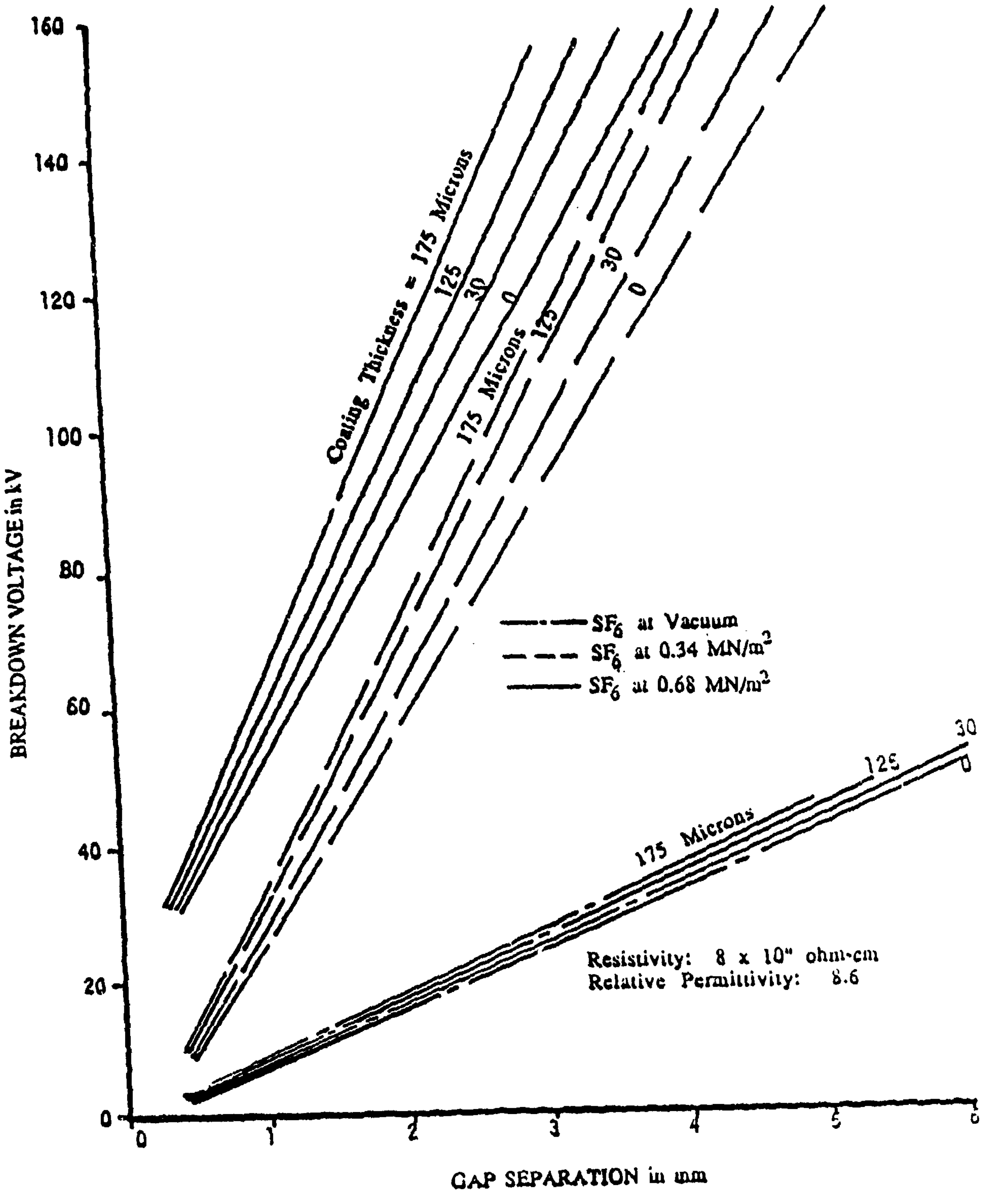


Figure 8. Performance of Anodized Aluminum Electrodes Under DC Voltages

Metallic impurity particles can greatly reduce the breakdown voltage in gas insulated systems. This effect becomes more pronounced with increasing pressure and particle length (Figures 9 and 10). The particles become charged in the field and move between the electrodes. The field nonuniformity at the particle initiates low voltage breakdown (References 18, 19, and 23 through 26). Particle traps can be used to remove the particles and reduce their effect on breakdown.

3.1.3 Voltage Transients and Time Lag. The time lag to breakdown is the sum of (1) statistical time lag, which is the time it takes for the initiating electron to appear in the gap; and (2) the formative time lag. The formative time lag can be interpreted as the sum of two parts: the time for the electron avalanches to form or to reach a critical value, and the time for the highly conducting spark channel to be formed by thermal ionization sufficient for voltage collapse (References 3, 8, and 20).

The time to breakdown varies with the applied voltage, the gas pressure, the electrode configuration, and the spacing between electrodes. Curves showing the ratio of impulse voltage to steady-state breakdown voltage for the electrode configuration in air at one atmosphere pressure is shown in Figure 11. This curve shows that very fast, short-duration transients (less than 10 ns) will not cause breakdown at overvoltages less than 150 percent of steady-state breakdown voltage. Slow transients (on the order of 1μs duration) require 105 percent to 110 percent of steady-state voltage for breakdown. Thus, the transient voltage peak and duration are important elements in estimating the probability of breakdown between electrodes of known configuration.

3.2 Liquid Dielectrics. Liquid dielectrics may be used as insulators and as a heat transfer medium. Often, liquid dielectrics are used in conjunction with solid insulations such as papers, films, and composite materials. By eliminating air or other gases, liquid dielectrics improve the dielectric strength of the insulation system. Liquids are also self-healing, in contrast to solid dielectrics. The affected area of a failure caused by a temporary overvoltage is immediately reinsulated by fluid flow back into the affected area.

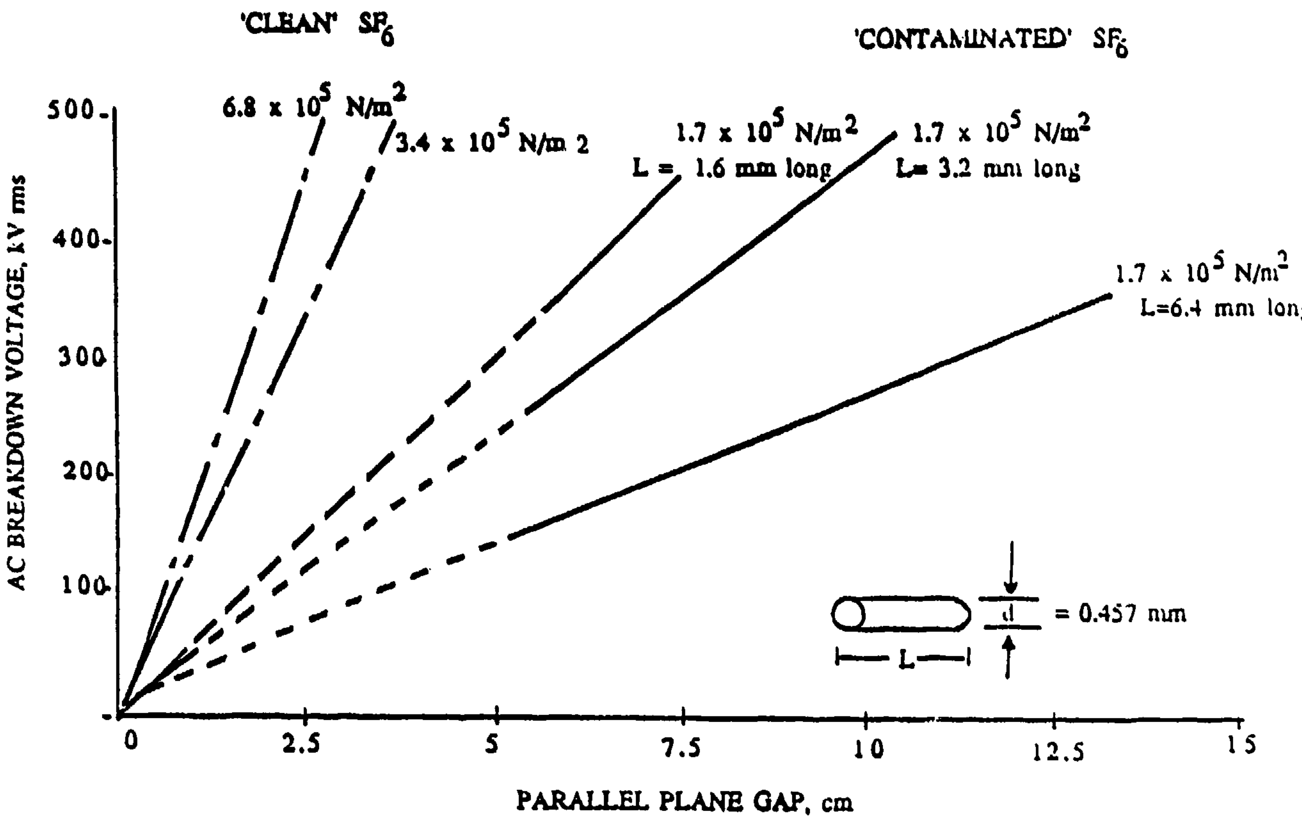


Figure 9. AC Breakdown Voltage-Gap Characteristics in SF_6 with Copper Particles of Various Length

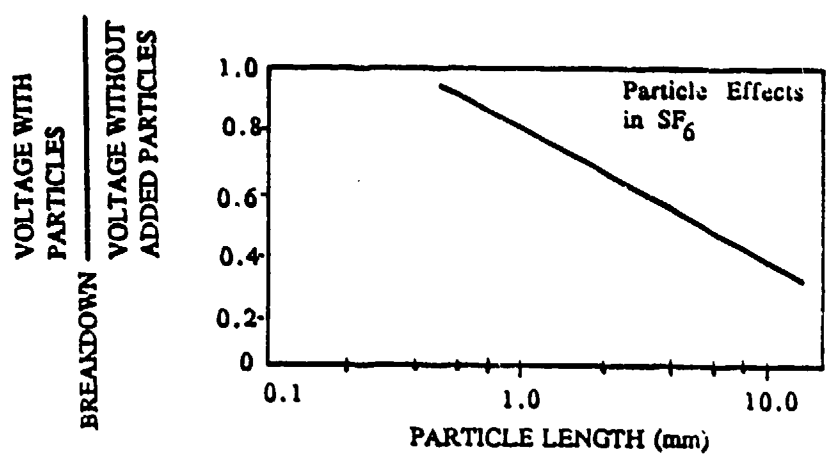


Figure 10. Reduction in SF_6 Breakdown Voltage Due to Conducting Particles at 1 Atmosphere

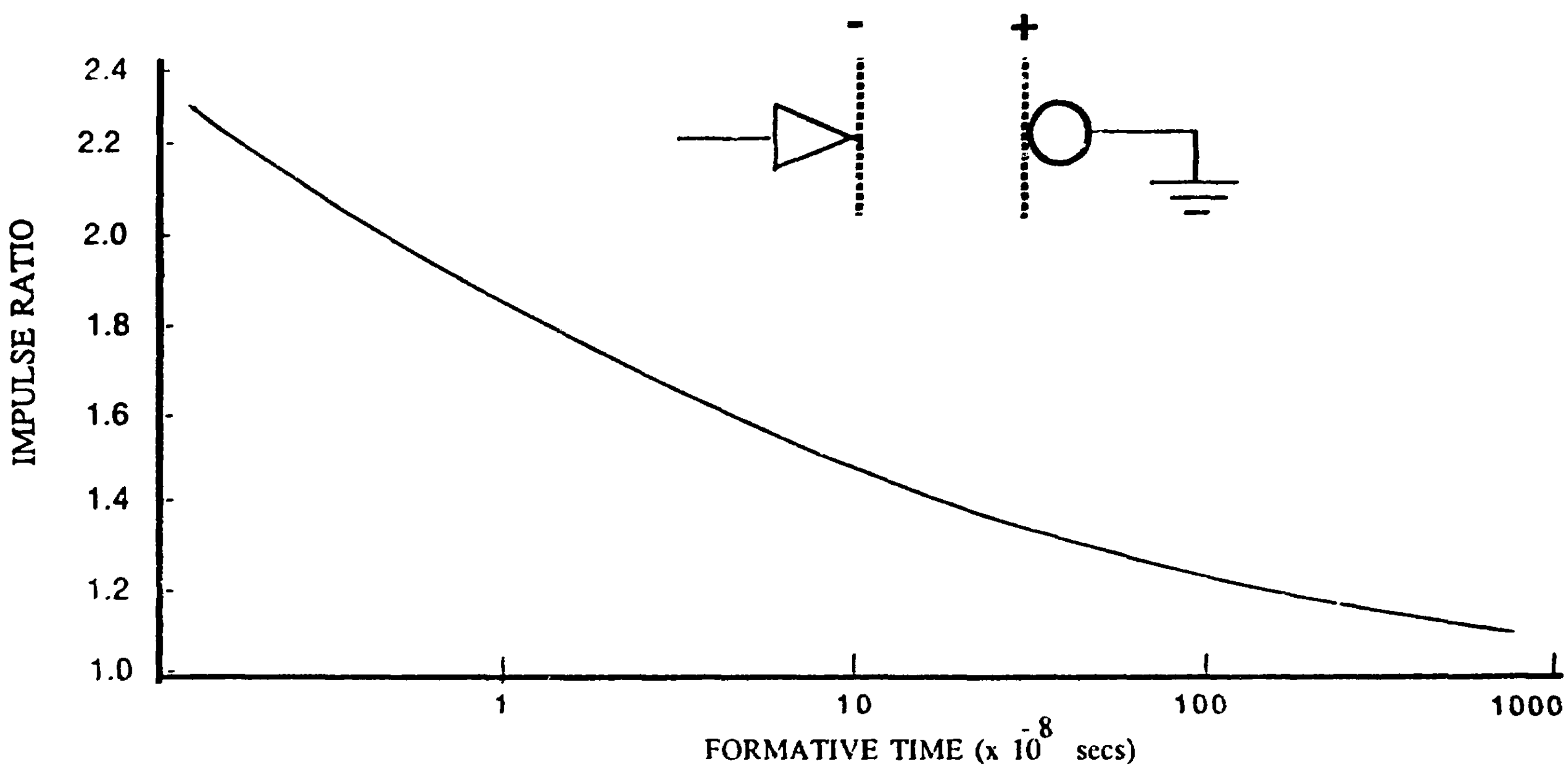


Figure 11. Relation Between Formative Time and Impulse ratio for Various Gap Lengths and Gas Pressure in a Negative Point-Sphere Gap in Air

Liquids used as insulators are mineral oils, silicone oils, fluorocarbons (fluorinated liquids), vegetable oils, organic esters (including castor oil), and polybutenes (polyhydrocarbon oils). Polybiphoenyl carbonates are environmentally unacceptable and should not be used.

3.2.1 Selection. To select a liquid dielectric, its properties must be evaluated in relation to the application. The most important properties are dielectric strength, dielectric constant, conductivity, flammability, viscosity, thermal stability, purity, flash point, and chemical stability. Compatibility with other construction materials and the local atmosphere is critical.

Disadvantages that always accompany the use of liquid dielectrics are cost, weight, and operating temperature limits. Other disadvantages with many liquids are combustibility, oxidation, contamination, and reaction with materials in contact with the liquid. The deterioration of materials may generate moisture, evolve gas, form corrosive acids, produce sludge, increase dielectric loss, and decrease dielectric strength.

The characteristics of some typical liquids (References 27 and 28) used for high voltage applications are provided in Table 7. Mineral oils are most commonly used for transformer or high voltage equipment insulation. Silicones are used for specialized applications when their fire resistance and high operating temperature characteristics are required. The other fluids are used with capacitor systems, when their high cost is justified by the superior performance required for the high voltage stress conditions typical in capacitors.

3.2.1.1 The Effect of Temperature. The operating temperature of a liquid dielectric affects its life and stability because chemical deterioration reactions proceed faster with increasing temperature. A pure liquid, in the absence of water or oxygen, should be very stable at rather high temperatures. The normal usable temperature range of liquid dielectric classes is shown in Figure 12. (Reference 29)

TABLE 7

PROPERTIES OF DIELECTRIC FIELDS

Property	Insulating Liquid							
	Mineral Oil	Dimethyl Silicone, 50 csec	Hydrocarbon Distillates MW 500-700	Isopropyl Biphenyl	Isobutyl* Monochloro Biphenyl Oxide	Di-2-ethylhexyl Phthalate-25 w/o Trichloro-benzene	Phenyl Xylyl Ethane	Di-2-Ethyl-hexyl Phthalate
Relative dielectric constant, at 60 Hz, 100°C	2.1	2.6	2.1	2.6	4.0	4.5	2.5	4.3
Dissipation factor at 60 Hz, 100°C, %	0.1	0.01	0.4	0.2	1.0	1.0	0.2	0.5
Dielectric strength ASTM-D877, kV	35	35	38	60	35	35	55	42
Gas absorption coeffic ASTM D-2300 μL/min	21	-13	-5	180	80	38	120	25
Viscosity at 100°F (37.8°C), csec	10	41	310	5.8	10.5	13	6.1	29
Pour point, °C	-55	-55	-20 to -30	-55	-45	-52	-48	-45
Fire point, °C	150	345	300	155	200	255	148	235
Use	Transformers, cables, circuit breakers	Fire-Resistant Transformers	Fire-Resistant Transformers	High Voltage Capacitors	High Voltage Capacitors	High Voltage Capacitors	High Voltage Capacitors	Low Voltage Capacitors

*No longer available.

Temperature also affects the conductivity of a liquid dielectric. As temperature increases, fluid viscosity decreases and the higher mobility of the ions permits increased conduction (Figure 13) (Reference 30). Refining techniques, additives, and blending of liquids are used to thermally upgrade liquid dielectrics (References 31, 32 and 33)

3.2.1.2 The Effect of Moisture. Water usually decreases dielectric strength (Figure 14) and increases dielectric loss (Reference 34). Moisture dissolved in pure mineral oil does not affect dielectric strength until it separates from the oil solution and deposits on conductors, solid insulation surfaces, or on solids floating in the oil. Oil invariably contains suspended fibers, dust, and other contaminates, so the presence of moisture usually lowers the dielectric strength. Polar contaminants dissolved in the oil give moisture its greatest degradation effect on dielectric strength.

Liquid dielectrics are used extensively to impregnate cellulosic insulations in transformers, cables, and capacitors. With these applications the rate of increase of water solubility in the liquid with increasing temperature is important. When the rate increase in water solubility in the liquid is different from that in the cellulosic insulation, changes in temperature can make the dissolved water separate from the liquid. Such a separation leads to the formation of liquid-water emulsions and severe dielectric degradation.

3.2.1.3 Dissolved Gas. The effects of gas absorption and liberation in a liquid dielectric must be considered for long-term, successful operation (Reference 35). This is especially true when the liquid is used to impregnate solid dielectrics, as in capacitors and cables.

Changes in pressure can make dissolved gasses evolve from a liquid. Also, temperature affects the solubility of gas, so heating can cause dissolved gas to evolve from the liquid. Corona will start in the evolved gas bubbles, leading to eventual dielectric breakdown. Thus, liquids used as impregnates must have a low, stable gas content.

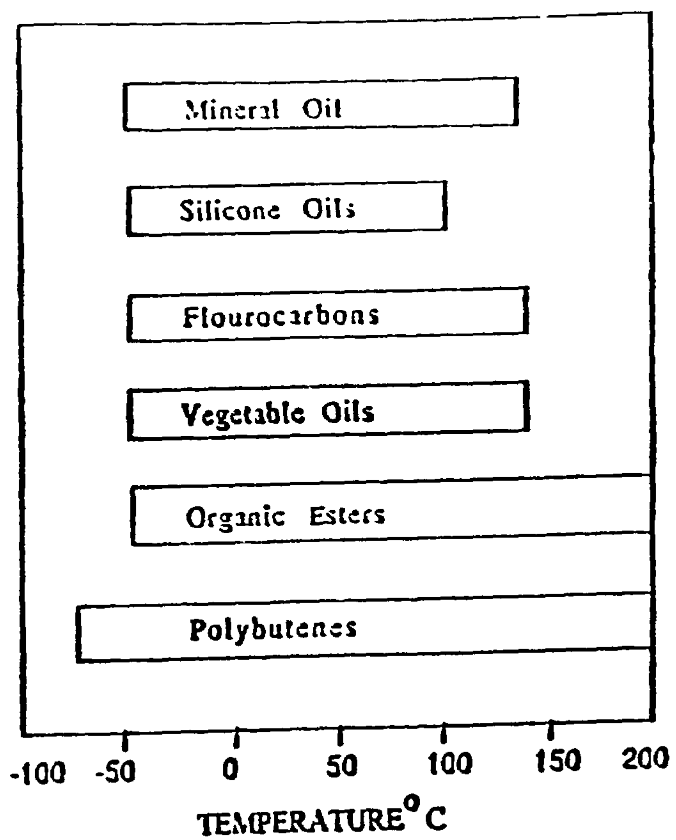


Figure 12. Normal Usable Temperature Range of Liquid Dielectric Classes

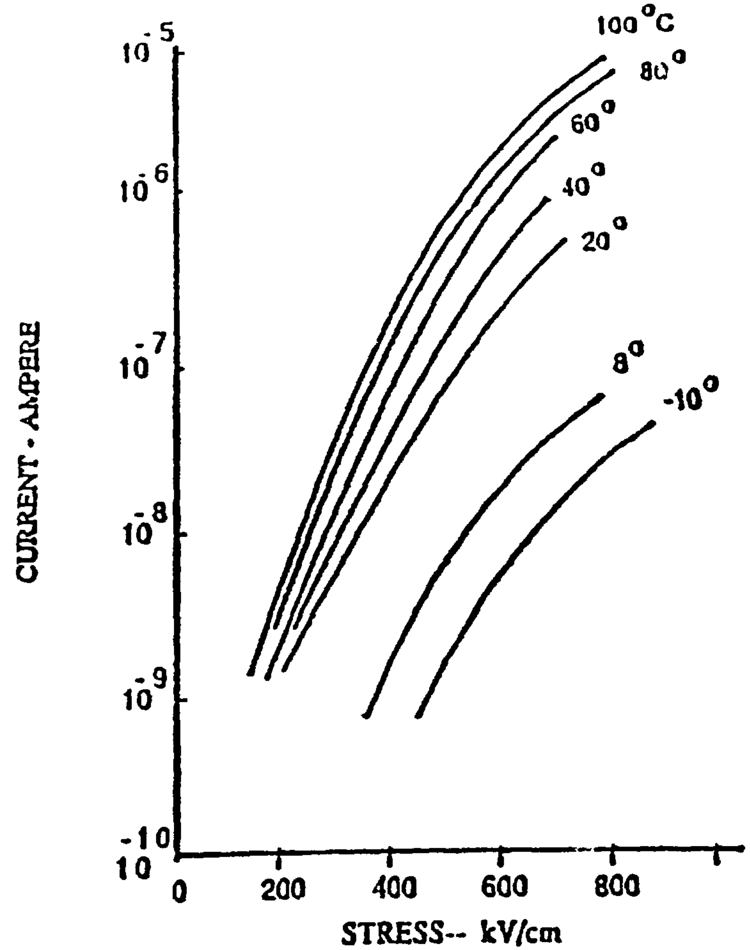


Figure 13. Effect of Temperature on Conduction Current in Degassed Transformer Oil

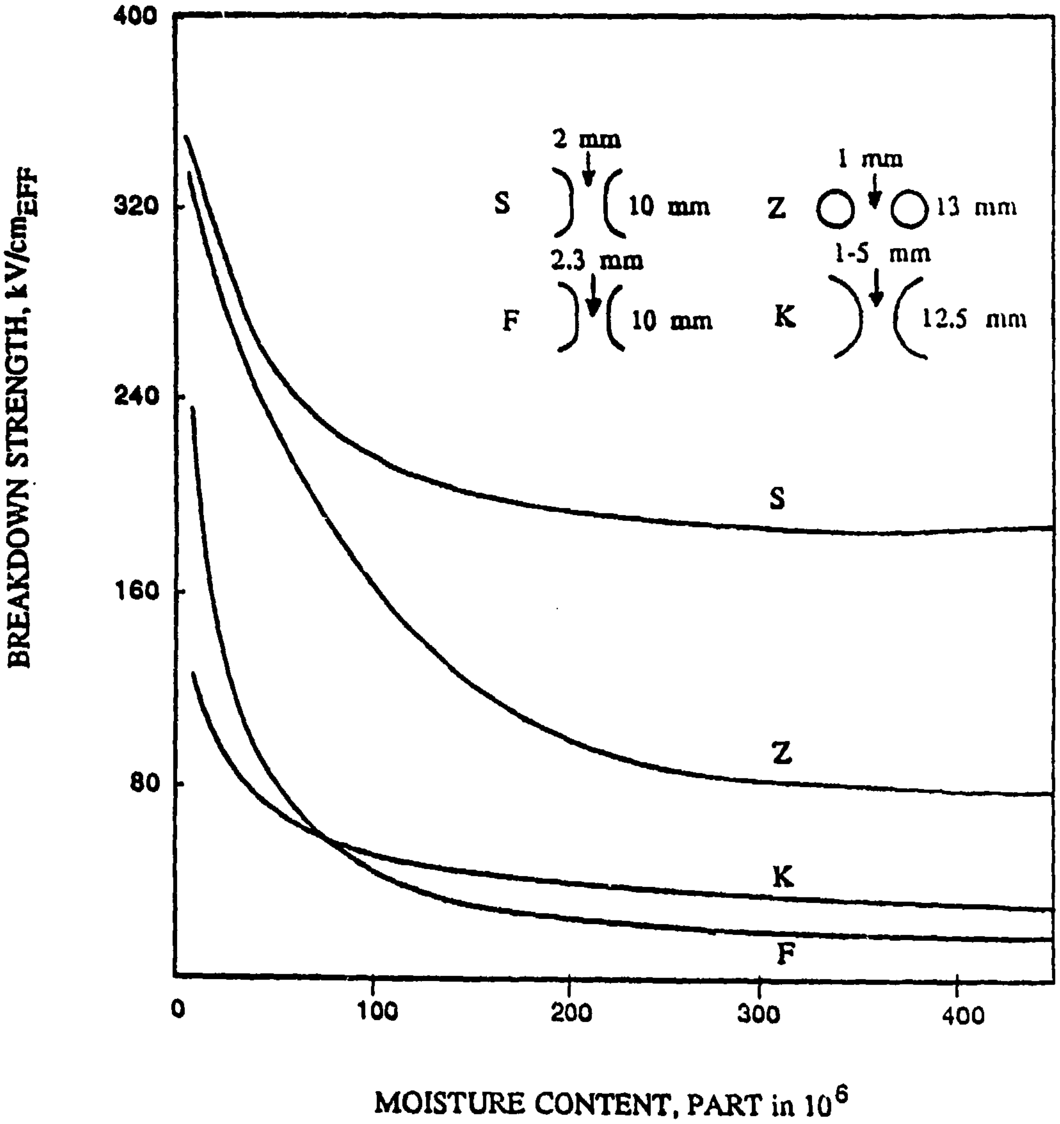


Figure 14. Effect of Moisture Content on Breakdown Strength in Mineral Oil.

3.2.2 Breakdown Phenomena. Parameters affecting dielectric breakdown in insulating liquids include electrode materials, electrode surface area and shape, manufacturing treatments, contamination, and deterioration. Typical breakdown voltage characteristics for mineral oil are shown in Figure 15 for various geometries (Reference 36). There is a significant "volume effect" for oil breakdown; that is, the breakdown voltage decreases with the volume of the oil under stress (References 37 and 38). It is assumed that electrical breakdown is initiated by "flaws," e.g., particles and imperfections, so that one has an extreme value breakdown voltage distribution. This results in the breakdown voltage decreasing with increasing volume under stress. Techniques have been developed to calculate the stressed volume of liquid for different electrode geometries and subsequently predict the breakdown voltage for other electrode configurations.

Liquid dielectrics deteriorate as they are contaminated by sludge, soaps, oxides, and condensation products. These contaminants form faster at higher temperatures and in the presence of reactants, catalysts, nitrogen, sulphur, and acids sometimes present in the liquid. Some of these contaminants are ionized. J. A. Kok (Reference 39) theorizes that colloidal ions with high permittivity drift toward the high electrical stress regions, where they form chains of dipoles bridging the electrodes.

3.2.2.1 Mineral Oil. Mineral oil is the most widely used of all liquid dielectrics. Typical characteristics of mineral oil used in common dielectric applications are shown in Table 8 (Reference 29). Because mineral oil is a product of crude petroleum, both the source and the refining process affect the end quality of the oil. The refining problem is to remove deleterious materials such as sulphur and nitrogen without removing or destroying the crude-oil constituents that appear to be necessary for long life and stability. Like inhibitors that are added during the manufacture of mineral oil, aromatic hydrocarbons slow down the rate of oxidation (Figure 16).

The contaminate products of oxidation reactions are sludge, asphalt, acids, organic esters, soaps, and oxides. Oil color, as an index of the degree of refinement for unused oils, is also a rough measure of deterioration of oil in service. Cloudiness indicates the presence of moisture, sludge, particles of

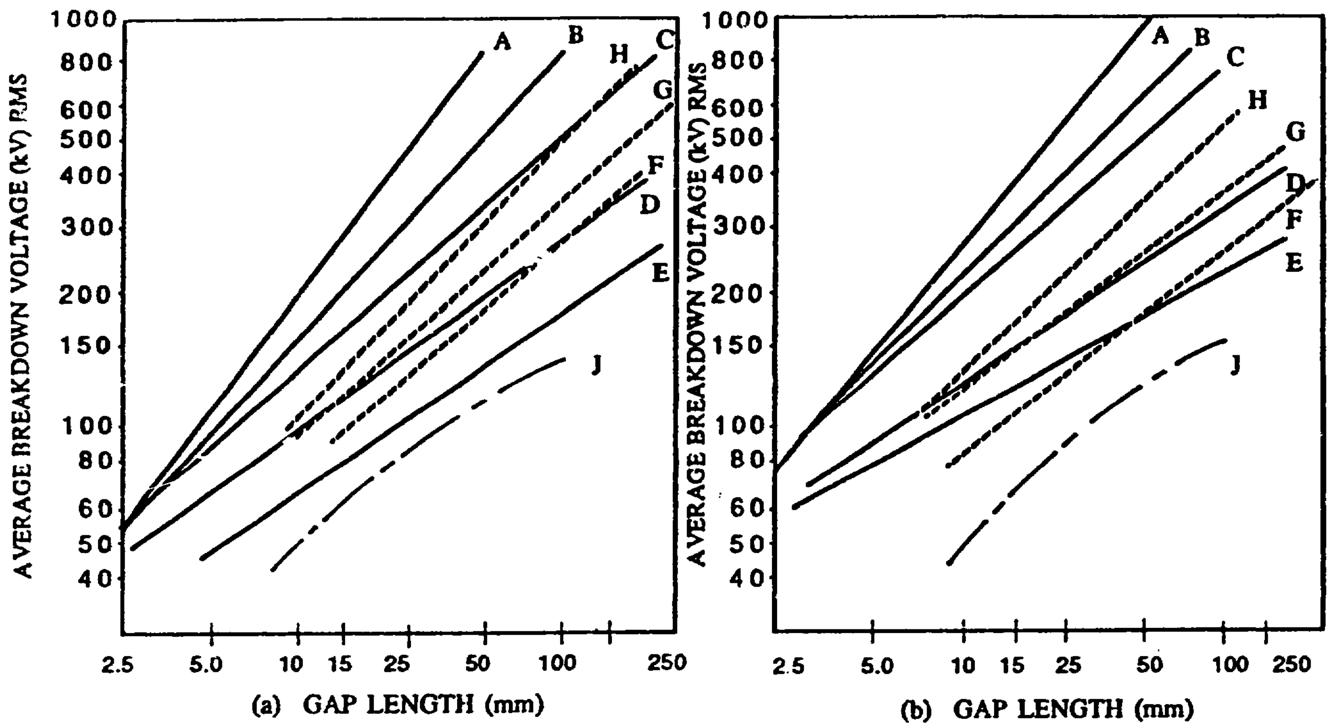


Figure 15. AC Breakdown Voltage Characteristics vs. Oil Gap Length in Various Electrodes.

(a) Steady Voltage Raising Method
(b) 1 Min. Withstand Voltage Method

A: 250 mmϕ Sphere-sphere
B: Plane-165 mmϕ Cylinder
C: Plane-34 mmϕ Cylinder
D: Plane-12 mmϕ Cylinder
E: Plane-6 mmϕ Cylinder
F: Plane-Sharp Edged Corner
G: Plane-Rounded Corner (5 mm Radius)
H: Plane-Rounded Corner (10 mm Radius)
J: Plane-30° Wedge

TABLE 8

THE AVERAGE CHARACTERISTICS OF MINERAL OIL

Property	For Use in Solid Type Cables	For Use in Capacitors and Hollow Core Cables	For Use in Transformers, Switches & Circuit Breakers
Condition	Clear	Clear	Clear
Viscosity	100"(98.9°C)	100" (37.8°C)	58" SSU (37.8°C)
Specific Gravity	.930 (15.5/15.5°C)	.885	.885(15.5/15.5°C)
Color	2.3 (NPA)	1 or less (NPA)	1 or less (NPA)
Neutralization Number	.02(Mg KOH/gram)	.02(Mg KOH/gram)	.02(Mg KOH/gram)
Flash Point (open cup)	235°C	165°C	135°C
Burn Point (open cup)	280°C	185°C	148°C
Pour Point	-5°C	-45°C	-45°C
Free Sulfur	nil	nil	nil
Total (fixed) Sulfur	.35%	.15%	.1%or less
Evaporation (8 hrs/100°C)	.....	.....	8%
Dielectric Strength	30 kv/cm	30 kv/cm	30 kv/cm
Specific Heat (30-35°C)	.....	.412	.4252
Power Factor (100°C)	.001	.001	.001
Chlorides and Sulfates	nil	nil	nil
Resistivity (100°C)	$1-10\times10^{12}$(ohm-cm)	$50-100\times10^{12}$(ohm-cm)	$1-10\times10^{12}$(ohm-cm)
Coef. of Expansion	.00075		.00070
Specific Optical Dispersion	115-120	115-120	110-115
Thermal Conductivity	.....	.....	.39 cal/cm/sec/°C
Refractive Index (25°C)	.....	.....	1.4828
Aniline Point	.....	.....	169°F(76°C)

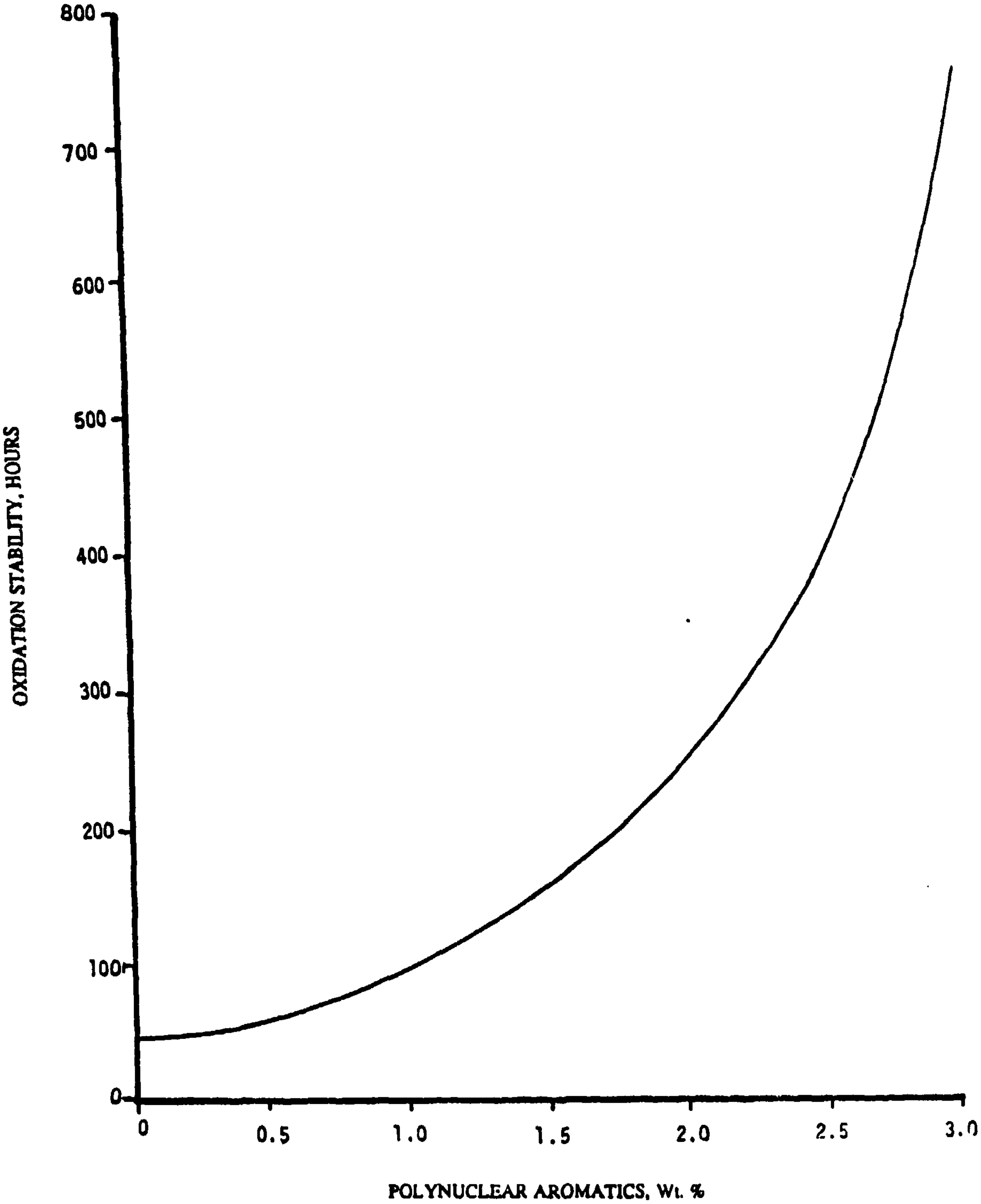


Figure 16. Oxidation of Transformer Oils in ASTM D943 Test. Hours to Interface Tension of 15 DYN/cm Versus Polynuclear Aromatic Content of the Oil

insulation, products of metal corrosion, or other undesirable suspended materials. Contaminants are introduced into mineral oils from:

- Improper manufacturing and refining methods
- Improper handling and shipping procedures
- Oxidation of the oil
- Soluable polar particles produced by moisture
- Leakage from the materials of construction or other insulations

Construction materials which may or may not be used in contact with mineral oils for long periods of time are shown in Table 9. The interfacial test is a sensitive detector of small concentrations of polar contaminates and oxides. This and other tests necessary in specifying electrical insulating oils are discussed by Clark (Reference 29) and by Simo (Reference 40). There are also new methods of accelerated testing and rapid measurement (References 41 and 42).

Three types of loss mechanisms are known to exist in mineral oils, all due to contaminates: (1) dipole orientation, (2) space-charge orientation, and (3) ionic conduction (Reference 43). The magnitude of each of these losses in an oil depends on oil temperature, frequency, oil viscosity, and the degree of contamination of the oil. These losses, particularly with respect to oil-impregnated paper, are discussed by Rogers (Reference 44) and Sakamoto et.al. (Reference 45) and Bartnikas (References 46 through 48).

New methods of refinement, new additives, new inhibitors, treatments, and new oil blends are being developed to improve critical parameters of oils without degrading the desirable electrical parameters in oil or oil-solid-dielectric insulating systems (References 49, 31, 32, 50, 51 and 52).

3.2.2.2 Silicone Oils. Silicone oils most commonly used as liquid dielectrics are dimethyl silicone polymers. These silicones are characterized by a nearly flat viscosity-temperature relationship, resistance to oxidation, stability at high temperature, and excellent high-frequency characteristics. They are unique in two important characteristics. The viscosity ranges from 1 to 1,000,000

TABLE 9

MATERIALS COMPATIBILITY WITH MINERAL OILS

Compatible Materials	Incompatible Materials
Alkyd resins	Acrylic plastics
Cellulose esters	Asphalt
Cork	Chloride flux
Epoxy resins	Copper (bare)
Masonite	Fiber board
Melamine resins	Greases
Nylon	Polyvinyl chloride resins
Phenol-formaldehyde resins	Rubber (natural & synthetic)
Polyamide-imides	Saran resins
Polyester-imides	Silicone resins
Polyethylene Terephthalate (Mylar)	Tars
Polyurethane	Waxes (petroleum)
Pressboard	
Shellac	
Silicone	
Wood	

ce tistokes, and they are stable for appreciable lengths of time at 150° to 200°C in the absence of air.

Silicone liquids resist oxidation and do not form sludge as do mineral oils. Their stability in the presence of oxygen makes them minimal fire and explosion hazards, even at temperatures up to 200°C.

3.2.2.3 Miscellaneous Insulating Liquids. Other liquid dielectrics include fluorocarbons, vegetable oils, organic esters, and synthetic aromatics. These fluids, several of which are new capacitor dielectrics (Table 7) are discussed in References 21, 28, 29 and 53.

Mammootty and Ramu (Reference 54) show that castor-oil-impregnated capacitors can be used at frequencies from 1 to 6 kHz. However, tan δ increases with temperatures at these frequencies and the capacitors must be cooled to prevent thermal runaway.

Experiments by Katahoire, et al. (Reference 55) show that silicone oil with cross-linked polyethylene spacers are a factor or two better than silicone oil testing with nylon spacers. The reduction of electrical stress with and without the spacer interface in silicone oil is shown in Figure 17.

It was found by Yasufuku et al. (Reference 56) that diarylalkane oil has excellent radiation resist- ce and is an excellent dielectric fluid for electrical apparatus operating in a radiation environment. It was also found in their experiments that sulfur compounds accelerated the corrosive action of the insulating oils. The evolution of gas is an excellent measure of a fluid's insulation integrity. A comparison of the gas evolution from mineral oils and diarylalkane after irradiating to 1.7×10^7R at room temperature is shown in Table 10. The viscosity change of the oils is shown after total gamma ray irradiation of 1×10^8R at room temperature.

3.2.3 Filtering and Outgassing. Oils used as liquid dielectrics should be filtered before use and outgassed when installed. Mineral oils, vegetable oils, and organic esters should be outgassed at 85°C and at a pressure of 10 Pa (0.7 torr), for 4 hours.

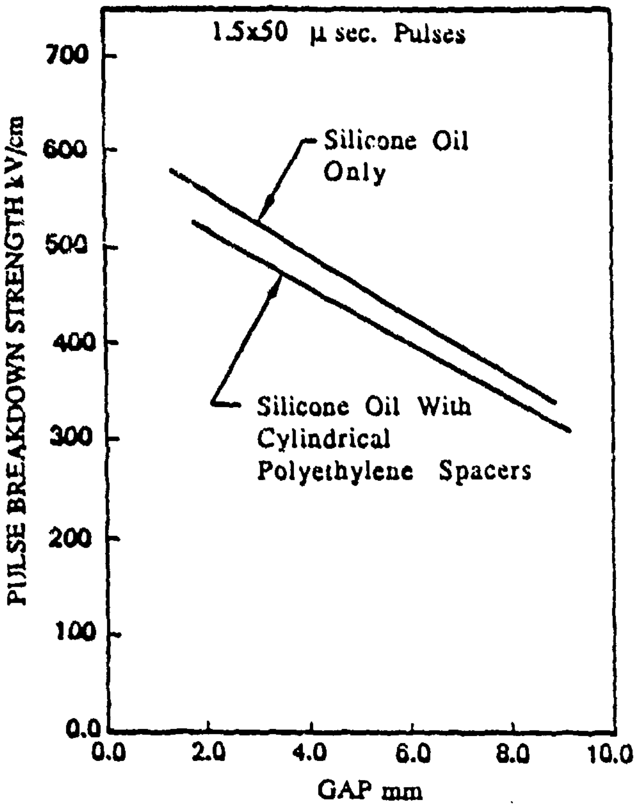


Figure 17. Silicone Oil Cross Linked Polyethylene Breakdown Under Standard Positive Pulse

TABLE 10

GAS EVOLUTION AND VISCOSITY CHANGE
AFTER GAMMA IRRADIATION OF
1.7 X 10^7R AT ROOM TEMPERATURE

		MINERAL OILS A	MINERAL OILS B	ALKYL NAPHTHALENE	DIARYL ALKANE
GAS EVOLUTION (ml/l)	CO	1.04	0.70	0.08	0.10
	CO_2	3.07	2.92	2.27	2.53
	H_2	296.52	252.76	21.75	8.28
	CH_4	15.51	23.22	2.72	0.94
	C_2H_2	0.06	0.08	0.03	0.03
	C_2H_4	4.85	3.98	0.08	0.00
	C_2H_6	5.54	4.15	0.12	0.00
	C_3H_6	2.07	1.28	0.31	0.00
	C_3H_8	2.86	1.56	1.77	0.00
	$i\text{-}C_4H_{10}$	0.02	0.15	0.01	0.00
	$n\text{-}C_4H_{10}$	0.02	0.03	0.00	0.00
	TOTAL	331.56	290.83	29.14	11.88
VISCOSITY AT 30°C, cS	0	14.00	11.95	21.70	6.69
	5×10^6R.	14.19	12.01	20.69	6.87
	1×10^7R.	14.19	12.03	20.17	6.87
	5×10^7R.	14.71	12.52	20.95	7.04
	1×10^8R.	15.15	12.90	21.76	7.13

Oils depressurized from 10^3 to 10^5 Pa (7 to 760 torr) have little change in conduction current at high voltage (to 680 kV/cm) where temperatures are below 50°C. At 50°C and higher, the conduction current increases as the pressure is decreased below ambient. This is caused by the release of dissolved gas, namely air and oxygen. Further experimental work in this field (References 57 and 58) has shown that the presence of air in oil reduces the affinity for dissolved gases in the oil with subsequent bubble formation. This fact alone presents a strong case for the thorough depressurization of oil.

Where possible, mineral oils that serve as high voltage dielectrics should be continuously circulated through activated alumina. Such filtering, by controling contamination, limits the loss of dielectric strength in mineral oils (Reference 29).

Contaminated oils that do not have the required properties are treated by centrifuging, paper filtration, or fuller's earth treatment. Treatment with fuller's earth removes oil-soluble moisture, acids, and other contaminants.

3.3 Solid Insulation. An ideal solid insulation has no conductive elements, voids, or cracks, and has uniform dielectric properties. Practical insulations have thickness variations, and may shrink with curing temperature and age. Further, they may have some deposited conductive elements, and their dielectric properties may change with temperature, frequency, and mechanical stresses.

In aircraft applications the environmental and electrical stresses vary as a function of time. Some parameters vary independently, others are synergistic. These variations make it difficult to select an ideal insulation for a specific application. It is important to note that it is not possible to extrapolate the operation of a second or third generation device based on the performance of a first generation device. For instance, the composition of materials varies from batch to batch. The cleanliness, manner of handling, and manufacturing in a production facility are not the same as in a prototype shop. All these factors must be considered when developing insulation for a new high voltage product.

The pertinent environmental and electrical characteristics of solid insulations are discussed in the following section.

3.3.1 Materials Properties. Table 11 summarizes the electrical, mechanical, thermal, and chemical properties that need to be considered for solid insulation. Sometimes solid potted insulation is specified to be transparent so that the packaging engineer can assess parts stressing and bonding. Weight, water adsorption, and outgassing are often specified. Most important for all categories of high voltage insulation is life, which is dependent upon the electrical stress and environment.

Dielectric strength, dielectric constant, and the dissipation factor are the most readily measured electrical properties. Dielectric strengths and dielectric constants are well documented for high voltage materials. Fewer data are available on the dissipation factor, also called loss tangent, which is defined as:

$$\tan \delta = \frac{\sigma}{\omega \varepsilon} = \frac{1}{Q}$$

where σ is the ac conductivity, and ω is the frequency in radians/s and

$$Q = 2\pi \frac{\text{Average energy stored per half cycle}}{\text{Energy dissipated per half cycle}}$$

Dissipation factor and dielectric constant both vary with frequency and temperature, a characteristic that should not be overlooked.

For a dielectric with high resistance, its admittance, Y, may be written

$$Y = G + jB$$

and for vacuum as a dielectric,

$$Y_0 = G_0 + JB_0$$

TABLE 11

PROPERTIES OF INTEREST FOR INSULATING MATERIALS

MECHANICAL PROPERTIES	ELECTRICAL PROPERTIES	THERMAL PROPERTIES	CHEMICAL PROPERTIES	MISCELLANEOUS PROPERTIES
Tensile, compressive, shearing, and bending strengths	Electric strength	Thermal conductivity	Resistance to reagents	Specific gravity
Elastic moduli	Surface breakdown strength	Thermal expansion	Effect upon adjacent materials	Refractive index
Hardness	Liability to track	Primary creep	Electro-chemical stability	Transparency
Impact and tearing strengths	Volume and surface resistivities	Plastic flow	Stability against aging and oxidation	Color
Viscosity	Permittivity	Thermal decomposition, Spark, arc, and flame resistances	Solubility	Porosity
Extensibility	Loss tangent	Temperature coefficients of other properties	Solvent crazing	Permeability to gases and vapors
Flexibility	Insulation resistance	Melting point		Moisture Adsorption
Machinability	Frequency coefficients of other properties	Pour point		Surface adsorption of water
Fatigue		Vapor pressure		Resistance to fungus
Resistance to abrasion				Resistance to aging by light
Stress crazing				

but G_O = 0 in a vacuum, then

$$\frac{Y}{Y_o} = \frac{B}{B_o} = \frac{jG}{B_o} = k^* = k' - jk''$$

This ratio k* is called the complex dielectric constant or permittivity. The quantity

$$\frac{B}{B_o} = \frac{\omega C}{\omega C_o} = \frac{\varepsilon}{\varepsilon_o} = k'$$

and

$$\frac{G}{G_O} = \frac{C}{\omega C_O} = \frac{\sigma}{\varepsilon_O} = k''$$

where C = capacitance.

3.3.1.1 Dielectric Constant and Dissipation Factor. The effects of frequency on the value of the dielectric constant and dissipation factor at several temperatures are shown in Figures 18 and 19. There are frequency ranges for which the dissipation factor is high and the dielectric constant varies. Sometimes the dielectric must be operated in a regime where the dielectric constant and dissipation factor are constant to avoid delectric heating and interelectrode capacitance changes. If the dielectric properties are functions of temperature, operating conditions must be highly controlled to provide stable and predictable performance.

Most measurements of dissipation factor are made at 1000 Hz and 23°C, but quite often the insulation must function between 400 Hz and 1 MHz and at 80° to 200°C. As a result, the designer has the problem of measuring the dissipation factor, searching for meaningful data, or extrapolating whatever data are available.

Referring to Figure 20, the sharp decreases in dielectric constant occur when the relaxation time of the particular polarization involved becomes equal to or less than the periodicity of the applied field. That is when $\tau \leq \frac{1}{F}$

Under such circumstances, polarization has time to get well under way and contribute to the dielectric costant. Conversely, when $\tau >> \frac{1}{F}$, the field reversals are too rapid and a polarization with that time constant cannot

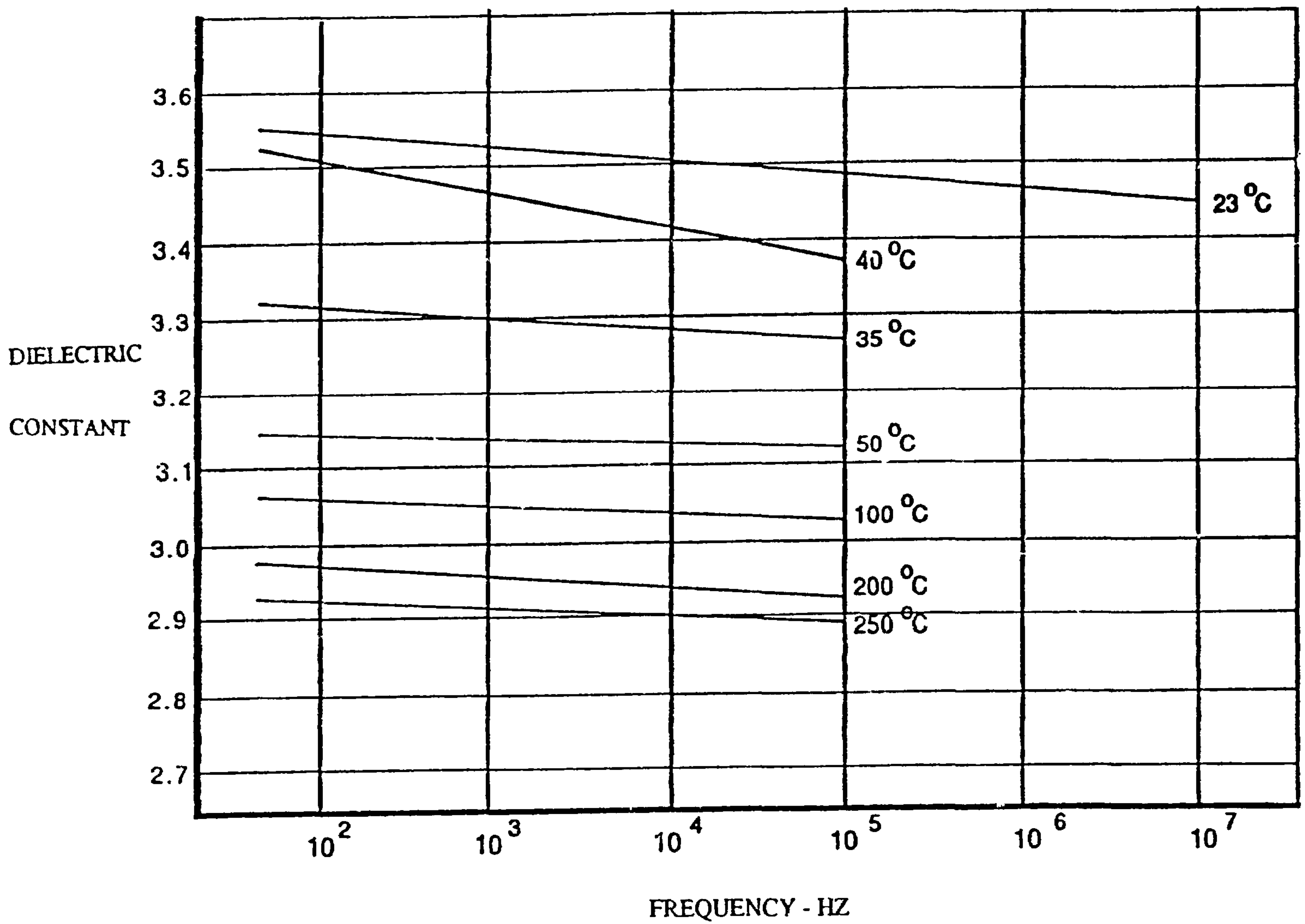


Figure 18. Dielectric Constant Vs. Frequency for 1 MIL Thick Type H Kapton Film

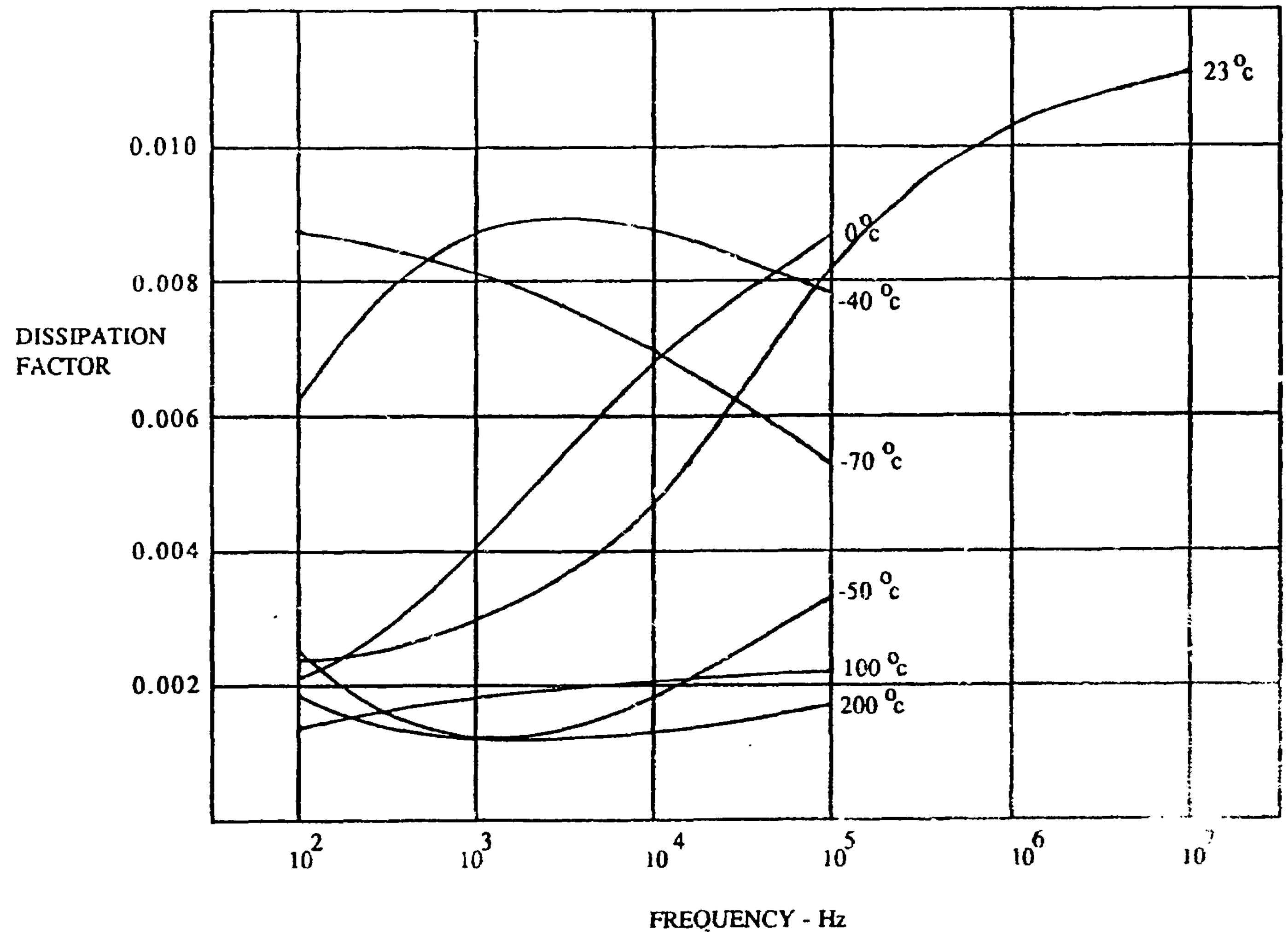


Figure 19. Dissipation Factor Vs. Frequency for 1 MIL Thick Type H Kapton Film

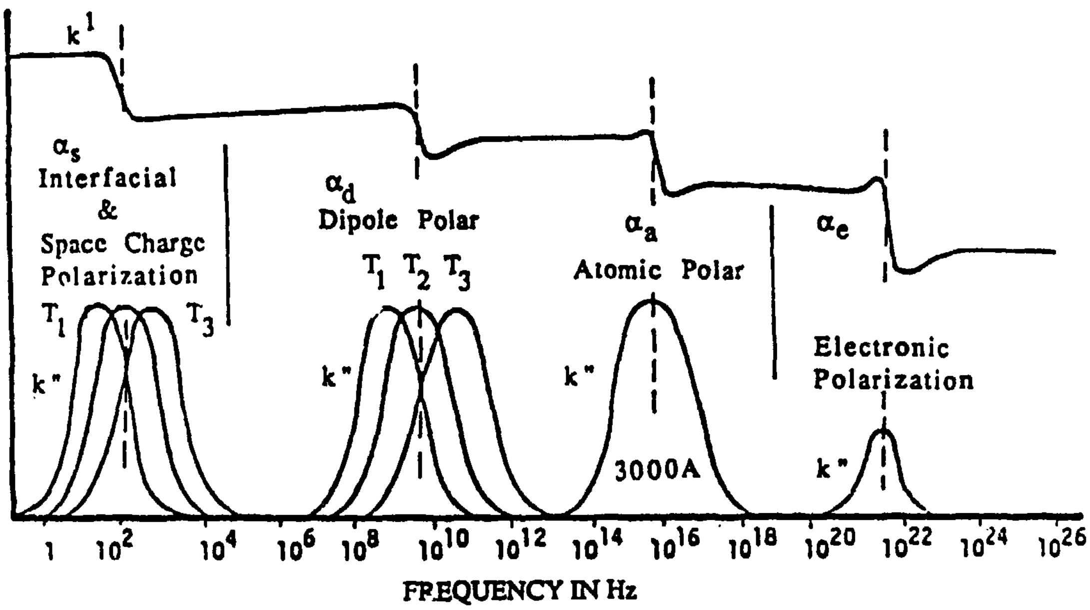


Figure 10. Dielectric Polarizations

contribute to total polarizability or to the observed dielectric constant. In general, α_s is effective up to several thousand Hertz; α_d can be effective from 10^4 up to 10^{12}Hz, and even this wide range can be increased further into the low-frequency area by reducing temperatures; α_a becomes effective in the infrared spectrum and α_e in the optical region and above.

Electronic circuits, if operated near the frequency singularities, can be affected by fluctuating interelectrode capacitance changes (References 5 and 59).

3.3.1.2 Polarization. A dielectric may have four abrupt changes in dielectric constant, the lowest value being at highest frequency and the highest value being at very low frequency, sometimes close to dc (Figure 18). Changes in the real part of the dielectric constant, k', are associated with significant change in the imaginary part of the dielectric constant, -jk": or the loss tangent.

3.3.1.3 Resistivity. A high volume resistivity reduces heating of the dielectric. Values greater that $10^{12}\Omega$-cm are adequate for most power equipment. High-voltage insulations should have a volume resistivity greater than $10^{14}\Omega$-cm. Polyamides in high voltage service should be operated at temperatures lower than 200°C, as suggested in Figure 21.

Surface resistivity must be greater than $10^9\Omega$-cm to prevent tracking and eventual flashover. New insulation usually has a surface resistivity greater than $10^{12}\Omega$-cm at 23°C and 50 percent relative humidity. This value is much lower with higher humidity and temperature. If the surface resistivity is reduced to 10^8 to 10^9 by contamination, a significant surface leakage current will flow This will dry out the surface and form a "dry band." The "dry band" will be bridged by a small electrical discharge because the stress locally will exceed the breakdown stress of air at the air-solid interface. Heat from the discharge will decompose the insulation and form a conducting path on the surface. With time, the paths will propagate, forming a tree, and breakdown eventually follows (Reference 60).

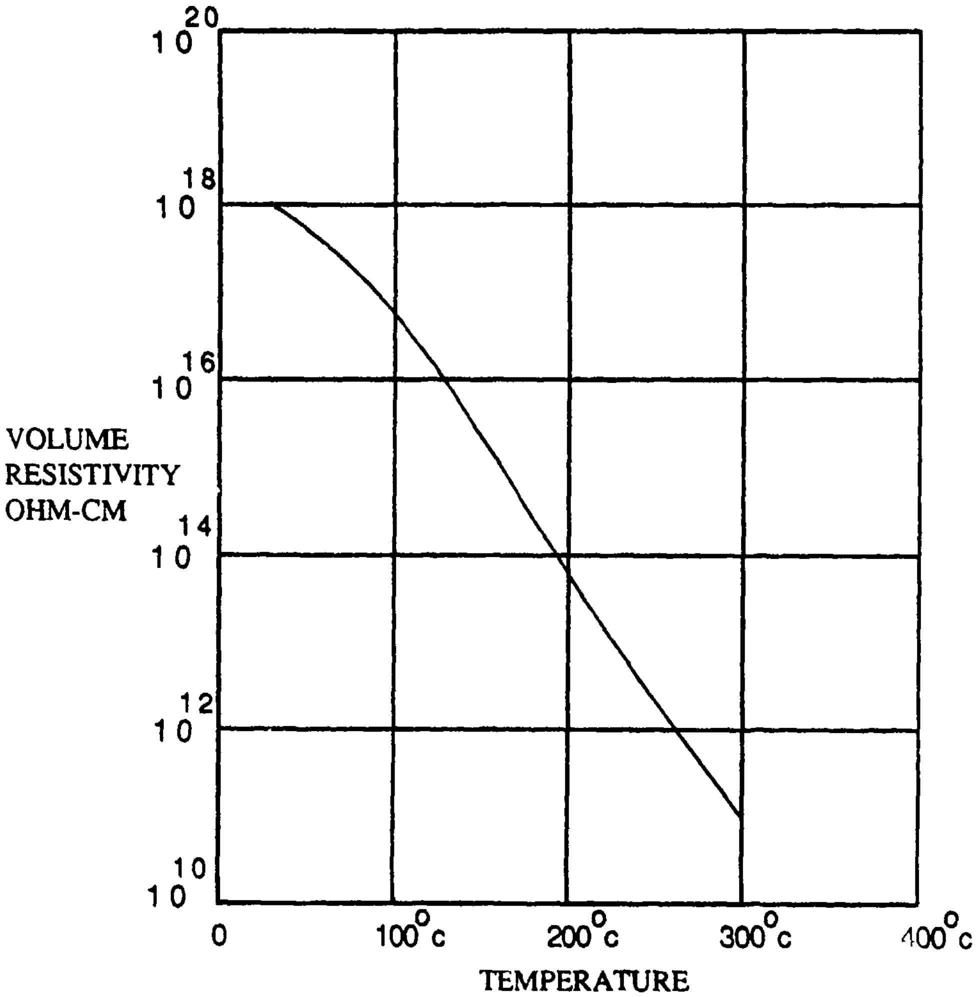


Figure 21. Volume Resistivity of Type H Kapton Film at 1 kHz Decreases as Temperature is Raised

3.3.2 Solid Materials Selection Data. When selecting an insulating material for a high voltage application, the right data seems to be hard to find. Mechanical and chemical data are usually abundant, but too often the available electrical data are a simple tabulation of constants, with no hint of how these constants will vary. Most published data need to be adjusted or translated for the application at hand.

The electrical properties of polyimide film (Kapton) are shown in Table 12. These variations in dielectric strength, dielectric constant, dissipation factor, volume resistivity, surface resistivity, and corona susceptibility are described below for Kapton H, a Du Pont polyimide often used as a high voltage insulation in aircraft. Throughout this paragraph English units of measurement are used to preserve consistency with the manufacturer's published data sheets.

3.3.2.1 Dielectric Strength. Typical values for the dielectric strength of Kapton H range from 7000 V/mil for a 1-mil film to 3600 V/mil for a 5-mil film, at 60 Hz. The values are for material placed between 0.5 inch-diameter electrodes at 23°C in air at one atmosphere pressure for 1 minute. The dielectric strengths quoted are based on statistical average breakdown of carefully manufactured, constant thickness polyimide films. These values are suspect for use in equipment design because:

- Films vary in thickness within manufacturing tolerances
- The composition of Kapton-H varies
- The operating temperature will not be 23°C
- Large-area thin films may have a few pinholes
- Voltage transients must be considered
- Field stress with other electrode shapes is different
- The end-of-life dielectric strength is lower

A more complete definition of the dielectric strength of Kapton-H is provided in Figures 20, 23, and 24. The effect of temperature on dielectric strength is shown in Figure 22. In aircraft applications, the highest average operating temperature for a unit is usually specified (85°C is typical). This temperature should not be taken as the insulation design value. The

TABLE 12

TYPICAL ELECTRICAL PROPERTIES OF POLYIMIDE FILM AT $23^{o}C$ AND 50 PERCENT RELATIVE HUMIDITY

Property	Typical Value	Test Condition	Test Method
Dielectric Strength			
1 mil	7,000 v/mil	60 cycles	ASTM
2 mil	5,400 v/mil	1/4" electrodes	D-149-61
3 mil	4,600 v/mil		
5 mil	3,600 v/mil		
Dielectric Constant			
1 mil	3.5	1 kilocycle	ASTM
2 mil	3.6		D-150-59T
3 mil	3.7		
5 mil	3.7		
Dissipation Factor			
1 mil	.0025	1 kilocycle	ASTM
2 mil	.0025		D-150-59T
3 mil	.0025		
5 mil	.0027		
Volume Resistivity			
1 mil	$1x10^{18}$ohm-cm	125 volts	ASTM
2 mil	$8x10^{17}$ohm-cm		D-257-61
3 mil	$5x10^{17}$ohm-cm		
5 mil	$1x10^{17}$ohm-cm		
Corona Threshold Voltage			
1 mil	465 volts	60 cycles	ASTM
2 mil	550 volts	1/4" electrodes	1868-61T
3 mil	630 volts		
5 mil	800 volts		
5 mil H/2 mil FEP/			
5 mil H/1/2 mil varnish	1,600 volts		

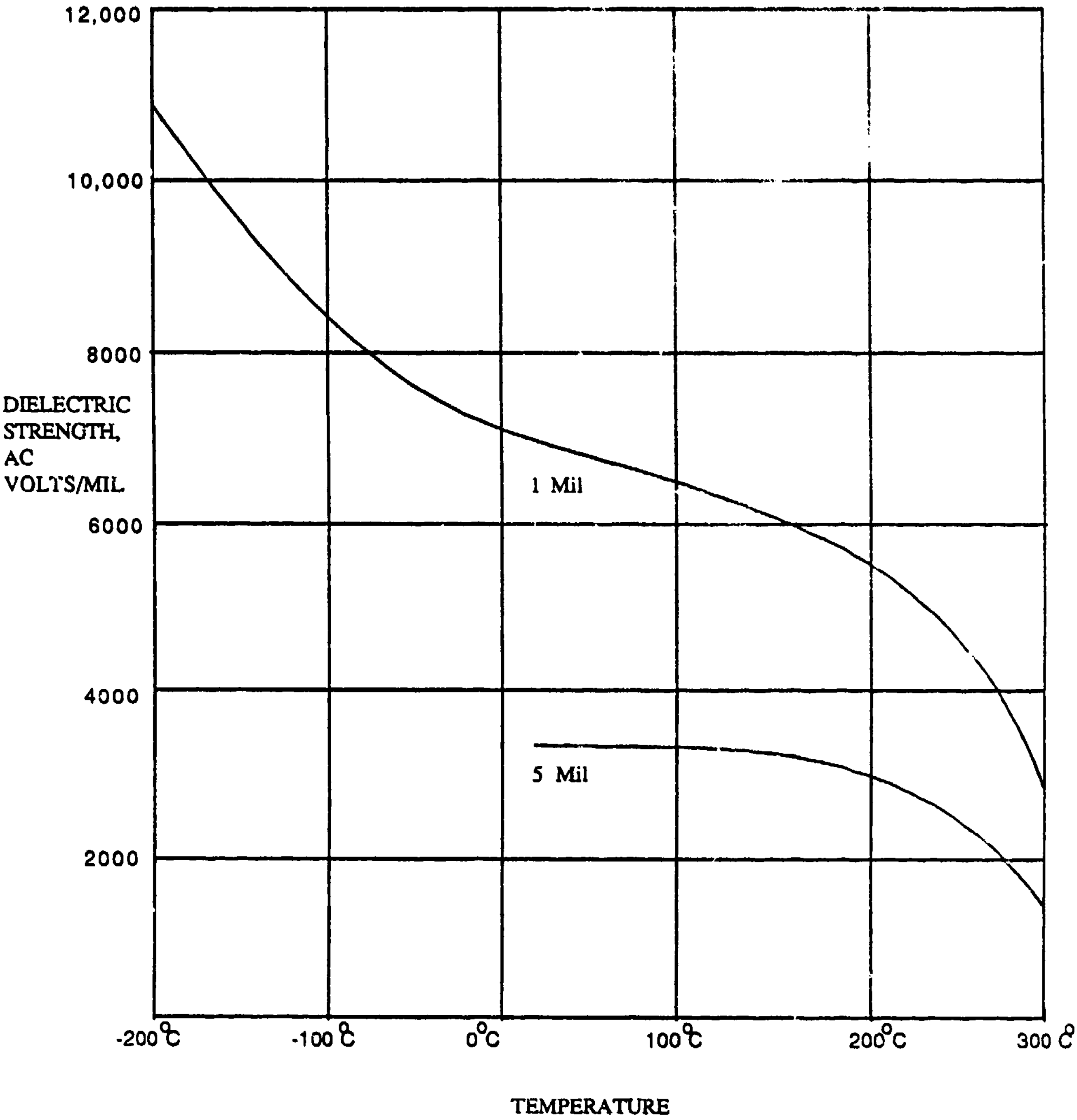


Figure 22. Temperature Affects AC Dielectric Strength Type H Kapton Film

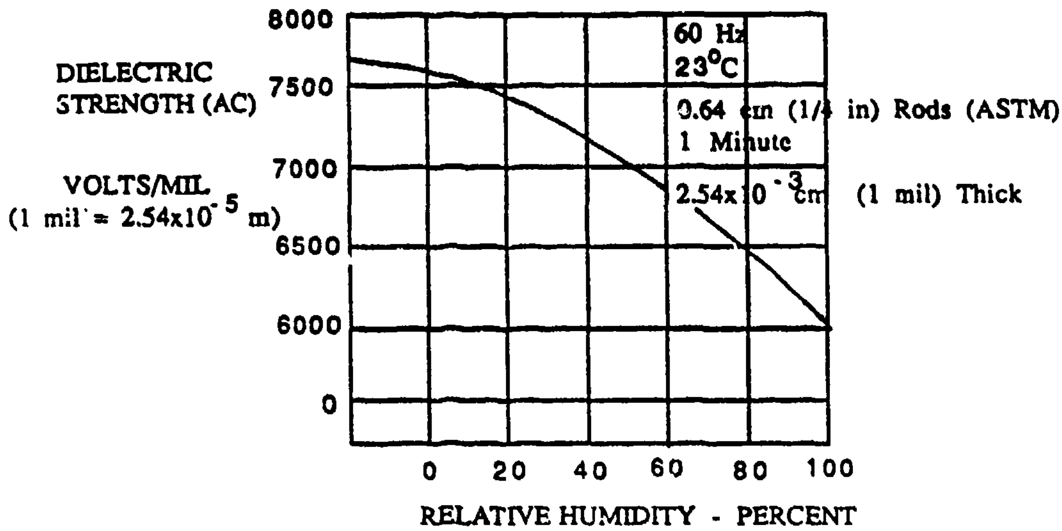


Figure 23. High Humidity Degrades the Dielectric Strength of Type H Kapton Film

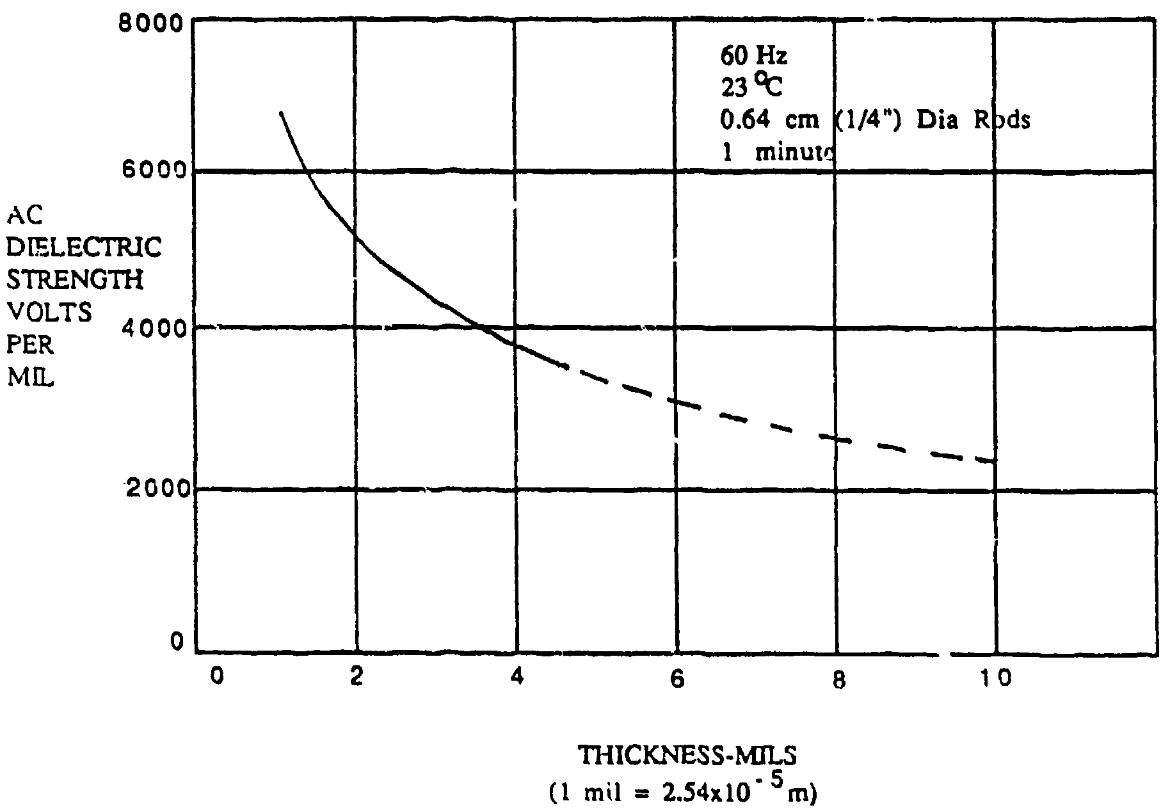


Figure 24. Insulation Thickness Affects Dielectric Strength of Type H Kapton Film

insulation design temperature must be that of the hottest point within the equipment. An electrically insulated heat-generating element will operate at a temperature that is sufficiently hotter than ambient to allow the generated heat to diffuse through the insulation. For instance, the hot spot near an electrical component may be 20°C higher than the nominal temperature in the insulation. Such "hot spots" are created by high current densities in wiring and heat generating mechanisms in the insulation itself. It is obvious from Figure 22 that an extra 20°C may lower the dielectric strength considerably when the insulation is either thin or operated at temperatures above 85°C.

Relative humidity also affects the dielectric strength of Type-H Kapton as shown in Figure 23. For this reason, very high voltage equipment is often packaged in sealed containers back-filled with a dry dielectric gas such as sulfur hexafluoride. Generally, insulation in dry gas has higher dielectric strength than in moist gas. Dielectric strength tests are usually made near 50% relative humidity.

Most insulation test samples are either 1 mil or 5 mil thick. In high voltage work, thin insulation doesn't have enough dielectric strength so composite insulations having several layers of thin insulation are required. The dielectric strength of insulation decreases with thickness, as shown in Figure 24.

Active area of insulation is a factor often neglected in literature and data sheets. For areas of a few square centimeters, the effect is small, usually requiring less than 5 percent derating. For large areas, the required derating is considerable, as shown in Figure 25. This loss of dielectric strength is caused by roughness of electrode surfaces and non-uniform thickness of the manufactured insulation.

3.3.2.2 Insulation Life. The most important factor in high voltage insulation design is the life of the material. The designer often has difficulty in finding data other than 1 minute tests at 23°C and 60 Hz between 0.5 inch-diameter electrodes. Such tests tell little about the long-life characteristics of the material. The life of Type-H Kapton polyimide is shown in Figure 26 for film

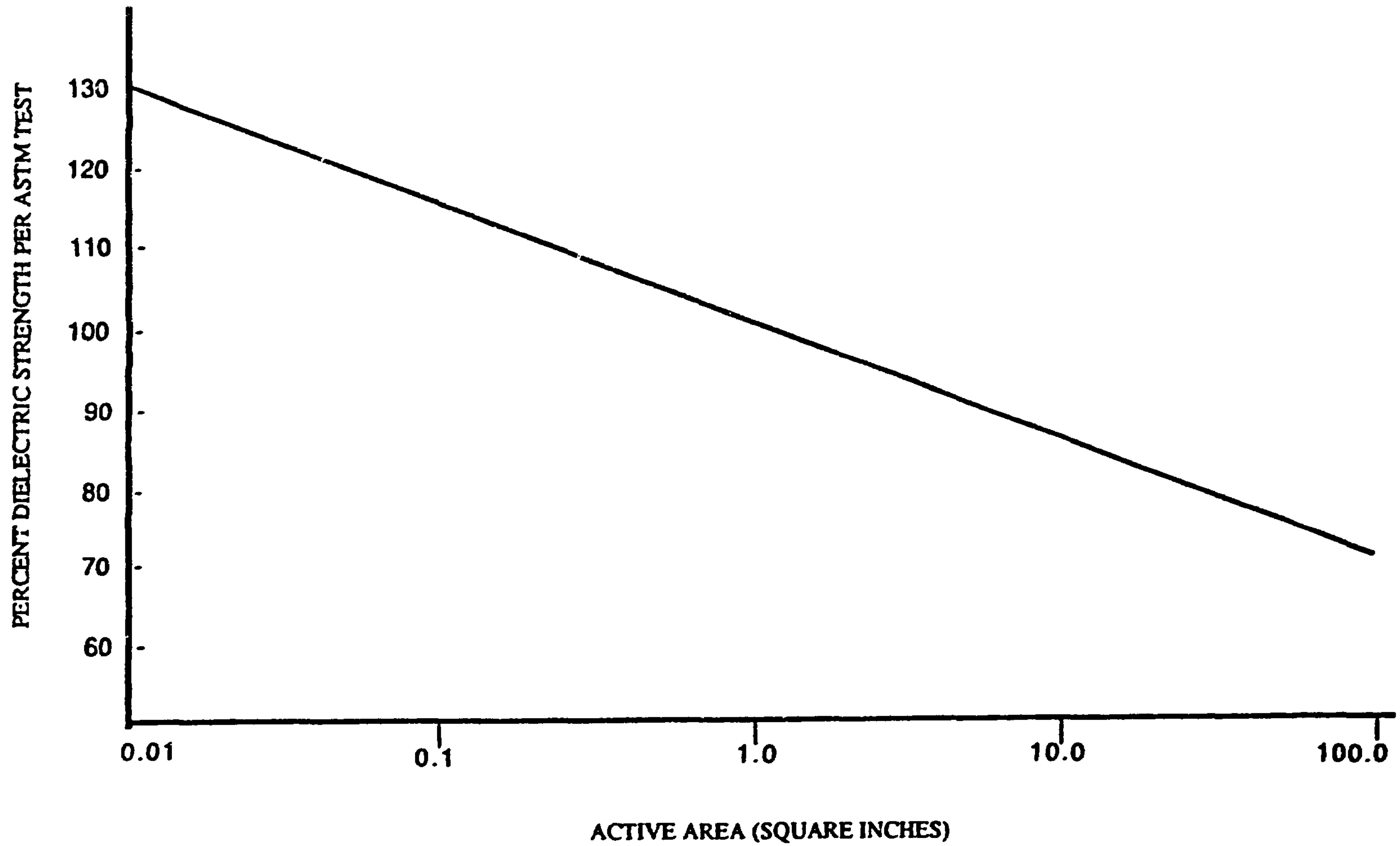


Figure 25. Film Area Vs. Dielectric Strength of Type H Kapton

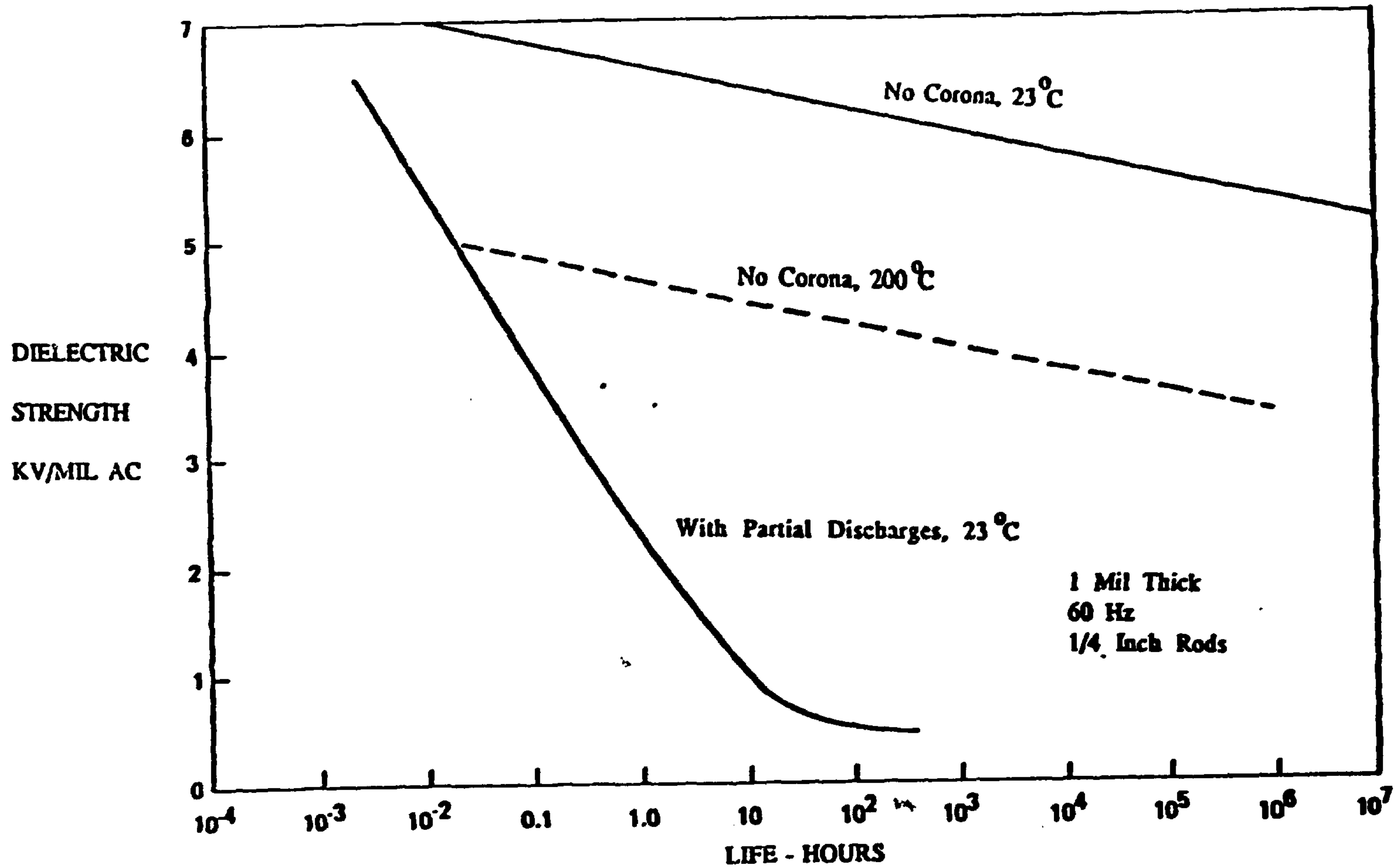


Figure 26. Life as a Function of Voltage for Type H Kapton Film

exposed and unexposed to partial discharges. With the exposed samples, partial discharges were present whenever the initiation voltage of 465 volts was exceeded.

The characteristic life of a material can be evaluated as a function of temperature when available data are plotted as an Arrhenius plot (Figure 27). Data for the life-temperature plot is taken as follows: (1) numerous samples are kept at constant test temperatures, (2) periodically a few samples are withdrawn and their breakdown voltages are measured, (3) when the statistically developed breakdown voltage of the withdrawn samples is 50 percent of the initial 1 minute breakdown voltage, the end-of-life is assumed to be reached for the specific sample at that temperature. Life testing must be conducted at several temperatures to obtain significant, useful data.

As a rule, the three generic-type encapsulating materials have maximum field stresses for 1 hour of operation, as shown in Table 13. The lower values are for very thick insulations. Higher values are for insulation less than 10 mil thick.

TABLE 13

ONE HOUR LIFE FIELD STRESS

Materials	Maximum V/mil Field Strengths
Epoxies	200 to 350
Silastics	300 to 600
Urethanes	250 to 500

Note that the data in Table 13 are for 1 hour life, not 10,000 hours. To obtain 10,000 hours the maximum stress must be decreased considerably. The voltage stress must be decreased by 8 percent to 10 percent for each order of magnitude increase in service life. For 10,000 hour the stress should be decreased to about 65 percent the values shown in Table 13. A generic curve that may help in design work is shown in Figure 28. This curve shows the voltage stress in volts per mil as a function of life. This generalized curve has already included many insulation derating factors norm.l to electronic

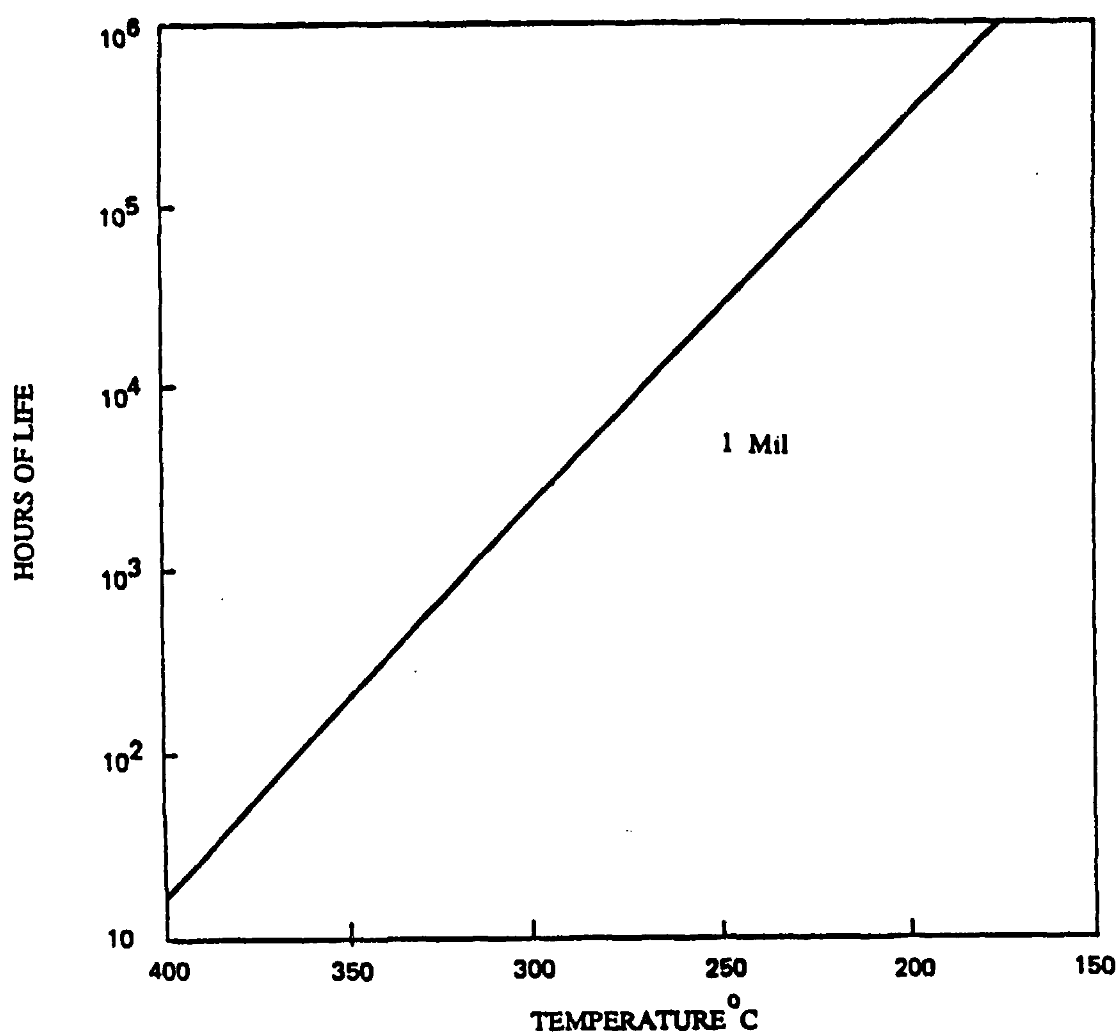


Figure 27. Heat Reduces the Time for Kapton Type H Film to Fall to Half of Original Dielectric Strength

Baseline: Dielectric Strength = 7000 V Per Mil for 1 Square Inch at 23° C, 50% RH and 60 Hz

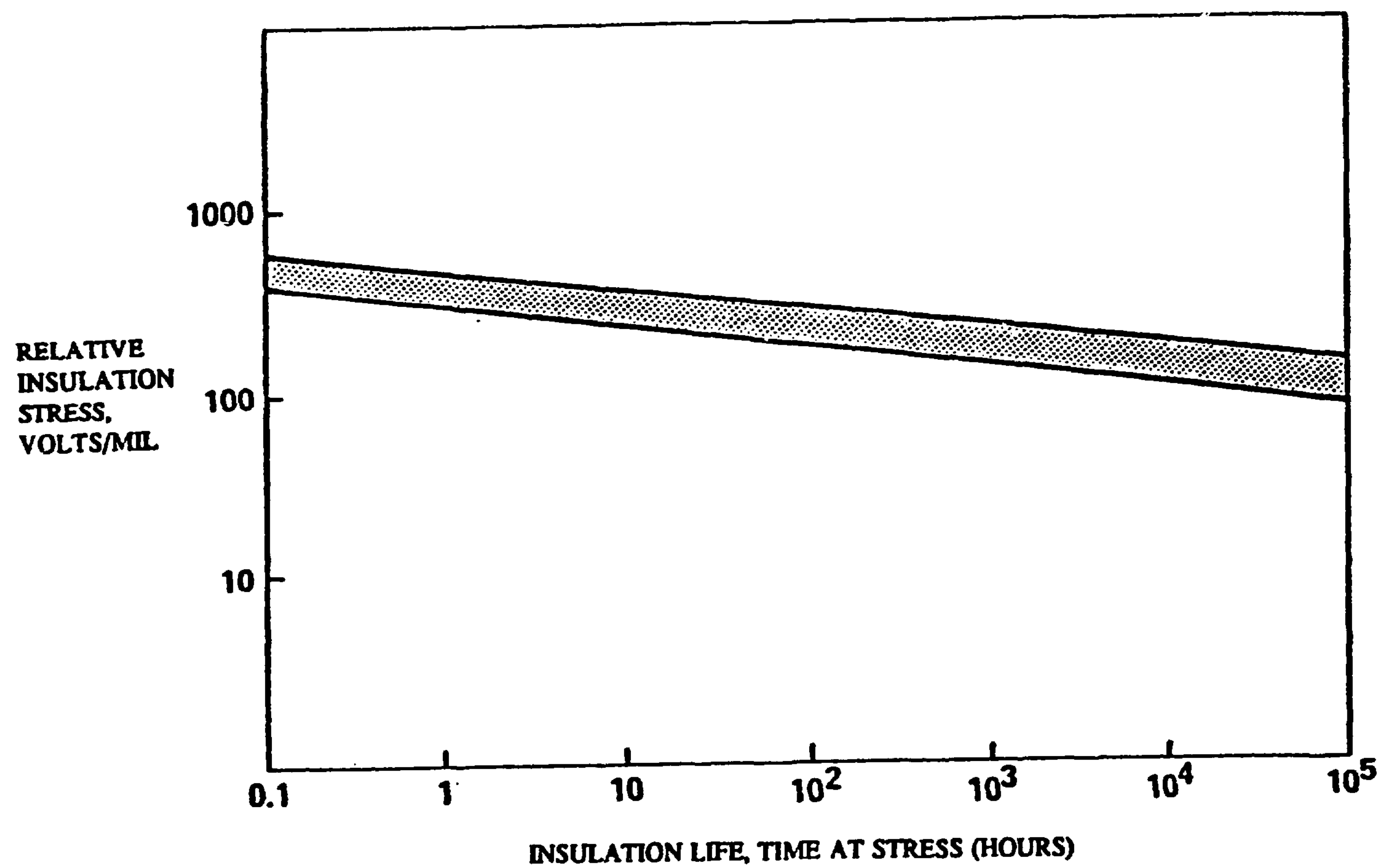


Figure 28. Insulation Life as a Function of Field Stress

circuits. Not included are frequency, temperatures greater than 85°C, and units with volumes greater than 500 in^3.

Factors that significantly decrease insulation life are improper materials preparation, encapsulation, bonding, and voids. Use of the term "void-free" to describe an electrically insulated set of electrodes does not imply the insulation is flawless; it means that the insulation is free of any "significantly large" voids. However, it must be remembered that as time passes and insulation deteriorates, small voids will increase in size, resulting in higher energy discharges and eventual insulation failure.

Another life degrading factor is frequency. Tests have shown that insulation life degrades inversely to the sinusoidal frequency or

$$L = 1/f$$

where L is life in hours and f is frequency in Hertz. When frequency, temperature, and voltage stress derating factors are all combined, it becomes easily understood how an insulation with 10,000 volts test at 1 minute can be reduced to less than a few hundred volts in application (References 61, 62 and 63). To further demonstrate the life temperature failure rate, the Arrhenius plot of insulation life as a function of temperature is shown in Figure 29.

3.3.3. <u>Cracks and Voids in Solid Insulation</u>. Voids and cracks within an electrical insulation vary in shape, smoothness, and composition, and each partial discharge produces chemical products that change the gas composition within the void, which subsequently modifies the surface of the crack or void. As a consequence, a set of theoretical models that can usefully predict the effects of partial discharges must be based largely on the manipulation of empirical data derived from tests using circuits such as those shown in Figure 30.

3.3.3.1 <u>Size, Shape, Location, and Distribution</u>. A precise count of the number of cracks and voids is very hard to obtain, requiring sectioning the dielectric sample and subsequently using optical techniques to determine density. Many cracks and voids would be unaccounted for or lost during the dissection

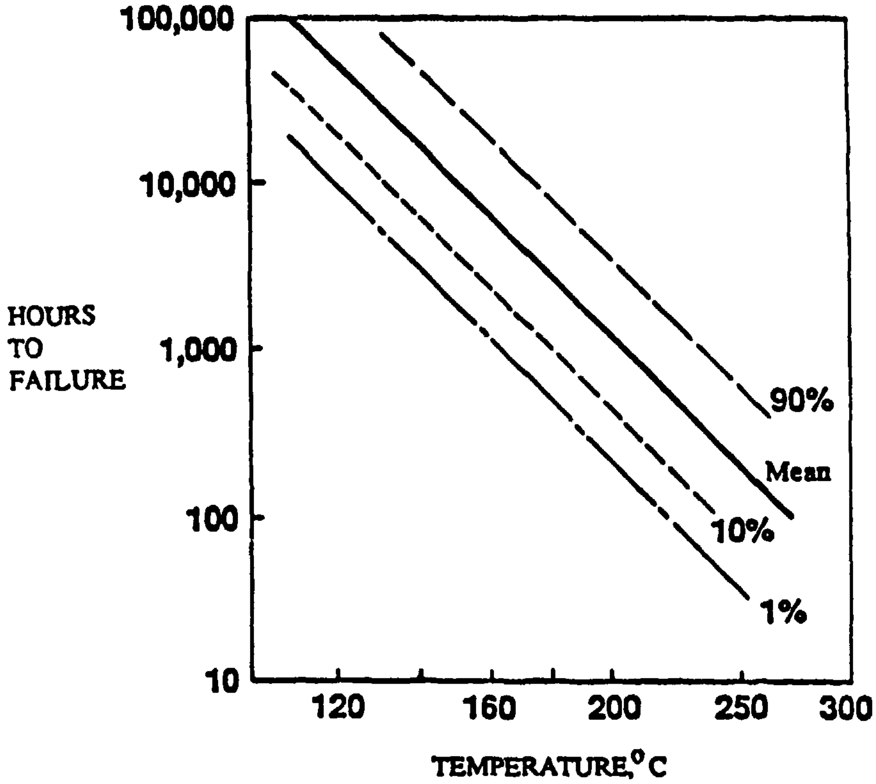
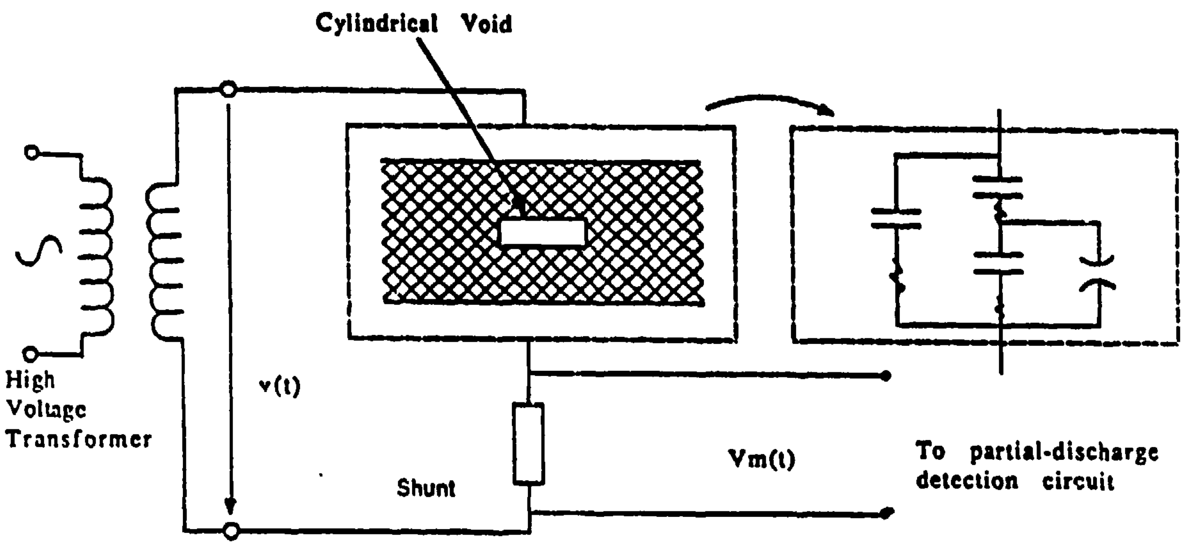
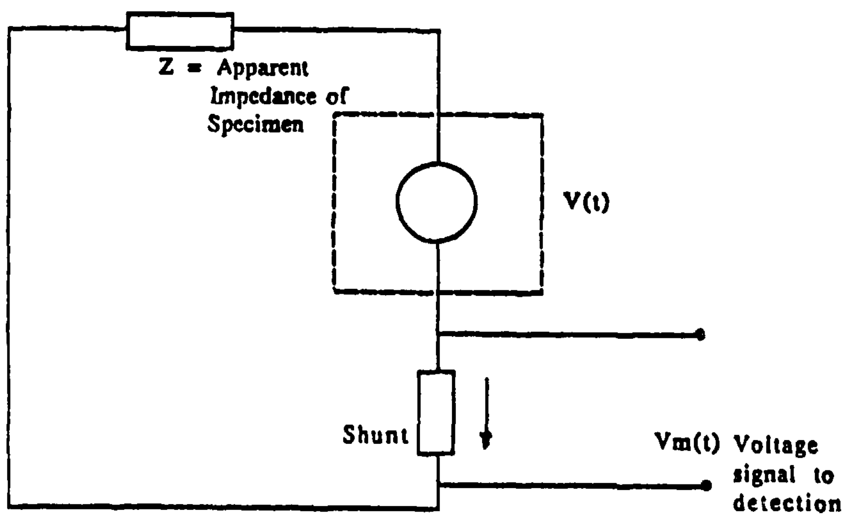


Figure 29. Arrhenius Plot of Insulation Life Versus Temperature for Class H Insulation



(a) Actual Circuit



(b) Equivalent Circuit For Pulses

Figure 30. Test Circuit for Measurement of Partial Discharges

process. It is easier to derive the size, shape, and general location of cracks and voids within the part or dielectric medium from non-destructive optical and electrical observations.

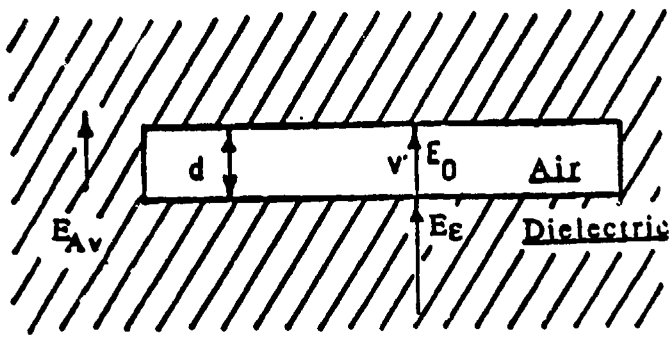
Cracks and voids are easily located in transparent and some slightly opaque materials with polarized light and a magnifying glass. Polarized light shining through the dielectric illuminates the cracks and voids, which then appear as bright curved surfaces, or bulges in the insulation. Slowly rotating the polarizing screen brings out other portions of the cracks and voids. This is a low-cost, effective method of detection. Interior cracks and voids become evident during electrical testing.

A void in a dielectric is an "island" having a dielectric constant that differs from that of the dielectric, thus altering the electric field in its vicinity. Figure 31 shows examples of dielectric stress augmentation in voids (Reference 64). The following symbols appear in the illustration:

E_o = voltage stress in the gas (disc)
E_ε = voltage stress in the dielectric in series with the gas-filled void
ε_r = dielectric constant of the material
E_{om} = voltage stress in the gas (sphere)
E_{av} = voltage stress across the solid dielectric
V = voltage stress applied to the void and dielectric

The worst case is that of the disc-shaped void shown in cross section on the top of the Figure 31. Here, with a width much greater than d, virtually all of the electric flux intercepted by the area of the disc (E_o x E_{av} x area) is forced to pass through or around the void. The stress in the gas dielectric necessary to sustain this flux is seen to be $E_0 = k\ E_{av}$ where k is the dielectric constant of the dielectric material.

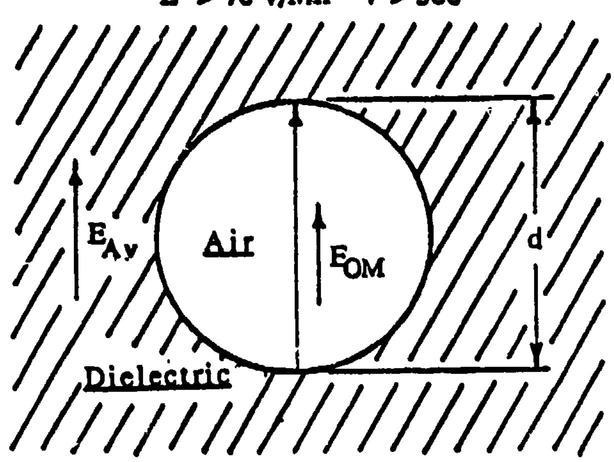
A spherical void is shown in cross section on the bottom of Figure 31. Here, part of the average flux in the solid insulation skirts the void while the remainder passes through the void. The effect, however, is such that maximum stress, E_{om}, always exceeds the average stress, E_{av}, as given by the formula in the figure. A value for polyethylene is shown. If the dielectric



Disc
Void

$$E_0 = \varepsilon_\gamma E_\varepsilon = 2.25\, E_\varepsilon$$

E > 70 v/Mil V > 300



Sphere
Void

$$E_{OM} = \frac{3\varepsilon}{1 + 2\varepsilon} E_{Av}$$

$$= 1.23\ E_{Av}\ \text{(Polyethylene)}$$

Figure 31. Stress Increase In Voids

constant of the material is increased, the field augmentation will increase proportionally for the disc-type void, but for the spherical void it is seen to approach a maximum value of 1.5 E_{av}. A low dielectric constant insulation will minimize the effect of voids.

The effect of void size will now be considered. The capacitance of a small disc-shaped void is

$$C_c = \frac{k\varepsilon_0 A}{d}$$

where k is the dielectric constant of the enclosed media (gas = 1.0), A is the area of the disc in square meters, d is the separation between the faces of the disc in meters, and ε_0 is the permittivity of evacuated space, $8.885x10^{12}$ F/M. The value C_c is important because it can be used in calculating the magnitude and energy of a pulse during a partial discharge in the void (Reference 65).

In the example shown in the sketch , the small capacitor C_c is instantaneously short-circuited. The consequent charge transfer is:

$$Q_c = \left(C_c + \frac{C_aC_b}{C_a + C_b}\right)\Delta V_c = \Delta V_c\left(\frac{C_aC_c + C_bC_c + C_aC_b}{C_a + C_b}\right)$$

where:

V_a = applied voltage

V_c = voltage across the void

C_a = capacitance of the total dielectric less that of the void and C_b

C_b = capacitance of dielectric in series with the void

C_c = capacitance of the void

Q_a = apparent discharge magnitude detected at the terminals, picocoulombs

Q_c = discharge magnitude in the void, picocoulombs

Simultaneously, a voltage pulse, which is effectively a step voltage having a risetime of between 10 and 100 ns, is generated at the terminals of the insulation:

$$V_a = \Delta V_c \left(\frac{C_b}{C_a + C_b}\right)$$

The apparent discharge magnitude, observed at the terminal, is :

$$Q_a = \Delta V_a \ C_a + \left(C_a + \frac{C_b C_c}{C_b + C_c}\right) = \Delta V_a \left(\frac{C_a C_b + C_a C_c + C_b C_c}{C_b + C_c}\right)$$

We can simplify the handling of the expression by letting:

$$C_3 = C_a C_b + C_a C_c + C_b C_c$$

Usually, a small area of the discharge site is almost completely discharged, so that:

$$\frac{Q_c}{Q_a} = \left(\frac{\Delta V_c}{\Delta V_a}\right)\left(\frac{C_3}{C_a + C_b}\right)\left(\frac{C_b + C_c}{C_3}\right)\left(\frac{\Delta V_a}{\Delta V_c}\right)\left(\frac{C_a + C_b}{C_b}\right)$$

$$= 1 + \frac{C_c}{C_b}$$

Most of the charge is released from the region where $\Delta V_c \to V_c$, so the energy liberated will be:

$$W = 1/2\, Q_c V_c = 1/2\, Q_a \left(1 + \frac{C_c}{C_b}\right) V_i \left(\frac{1}{1 + \frac{C_c}{C_b}}\right) = 1/2\, Q_a V_i$$

where:

W = energy in nanojoules

V_i = applied voltage in kilovolts (peak)

Q_a = charge in picocoulombs

Thus, we have a method of calculating the voltage, charge, and energy of a partial discharge in a void for a given applied voltage from the dimensions of the void and the dielectric constant of the surrounding dielectric.

A method of handling the distribution of voids was recently developed by S. Herabayashi, et al. (Reference 66). First, they analyzed a single void for initiating voltage V_s and charge Q caused by partial discharges. Second, the "void distribution function" M(d,s) was defined, with s the discharge area and d the gap spacing, assuming that many voids exist within the insulation whose gap spacings and discharge areas are d = d+dt and s = s+ds, respectively. The total number of voids (N_t) can then be described by the expression:

$$N_t = \int_0^\infty \int_0^\infty M^* (V_s, Q) dV_s dQ$$

where M* = is another void distribution function.

The number of partial discharges whose charge is $(Q_j - \Delta Q/2) < Q < (Q_j + \Delta Q/2)$ during a half cycle at ac voltage will be determined for each half cycle using a pulse height analyzer or similar recording device, giving the value N_{ij} which corresponds to $N(V_i Q_j)$. This expression can be then reformed to a reference equation as follows:

$$M^*(V_i, Q_j) = \frac{N_{i+1}{}^{j} - N_{i-1}{}_{j}}{V_{i+1} - V_{i-1}} - \frac{2}{V_i} N_{ij} + \frac{2}{V_i^2} \sum_{k=1}^{i} N_{kj} \left(\frac{V_{k+1} - V_{k-1}}{2} \right)$$

With this analysis tool, several types of partial discharges and other phenomena can be distinguished in test data. These phenomena include loose contacts (pulse at 0 voltage level) creepage paths (pulses with high magnitude at peak voltage and zero magnitude at zero voltage), small voids (single spikes), and partial discharges that have multiple spikes.

3.3.3.2 Material Dielectric Constant and Conductivity. The previous equation:

$$Q_c = \Delta V_c \left[\frac{C_a C_c + C_b C_c + C_a C_b}{C_a + C_b} \right]$$

indicates that for a given charge transfer, V_c depends on the capacitances C_a, C_b, and C_c. Because capacitance is $C_c = \frac{k\varepsilon_0 A}{d}$ each capacitance depends on the dielectric constant. The lowest voltage across the void will occur with short gap spacing and low dielectric constant. As the dielectric constant is increased, the field stress across the void increases, resulting in more and bigger partial discharges.

Insulating materials have very high volume resistivity, so conductivity has a negligible effect on partial discharges initiated by ac voltages. Conductivity is significant when a dc voltage is applied. The dc-circuit analog of the previous equation is obtained by substituting for

C_a = a fixed resistor of value R_a
C_b = a resistance of higher value R_b
C_c = a resistance of infinite value, or C_c

Applying a dc voltage across a very high resistivity dielectric produces these effects: (1) the initial distribution of the dc potential across the dielectric is related to the capacitance of its components, (2) in time, this distribution changes and is a function of the resistivities of the components of the dielectric, (3) initial space charges within voids dissipate, allowing partial discharges to occur and the breakdown voltage of the contained gas is exceeded, and (4) the discharge initiation and extinction voltages across the void depend on the temperature increasing as temperature decreases. For pure dc the discharge rate R is (Reference 67):

$$R = \begin{bmatrix} 0 & E_c < E_d \\ E\sigma/E_d k & E_c \geq E_d \end{bmatrix}$$

E = voltage across the dielectric
E_c = voltage across the void
E_d = initiation voltage for the gas-filled void
σ = bulk conductivity of the insulation

3.3.3.3 Gas Pressure and Composition. Before flight, the voids and cracks within unpressurized electrical insulation are at near Earth sea-level ambient pressure. In flight, the ambient pressure falls, but the pressure inside the voids decreases very slowly. In the meantime, the materials surrounding the void are backfilling the void with their outgassing, which may contain hydrogen, hydrocarbons, or halogens (fluorides). Some of these gases, particularly hydrogen and some hydrocarbons, have breakdown voltage lower than air (Figure 2).

Model voids used to evaluate insulations usually have gap thicknesses (dimension d) of 0.025 to 0.25 mm, which are representative of values found in practice (Reference 60). Voids as small as 0.0004 mm were measured in oil-filled paper capacitors. These voids were located in unimpregnated paper, between films and electrodes, and caused multiple failures, resulting in capacitor redesign to eliminate the voids. In those same capacitors, which had been designed for terrestrial use, the voids were found to be filled with a mixture of hydrogen and hydrocarbons from the oil and paper (Reference 68).

If the size of the void is known, then the Paschen-law curve can be used to calculate the voltage at which partial discharges will initiate. For example, with hydrogen the pressure-times-spacing factor is:

Pressure = 1×10^5 Pa at Earth ambient
Distance = 2.5×10^{-3} cm
Pxd = 250 Pa-cm

The voltage at which discharges will initiate across the void can then be obtained from Figure 2. For example, for hydrogen, V_c would be 300 volts. Conversely, if the applied voltage at which partial discharges occur is known, the above equations can be used to test for the presence of hydrogen.

The field strength within the void or crack will decrease with time as shown by K. Kikuchi, et al (Reference 69). These authors also found that the dc breakdown strength of cross-linked polyethylene decreased with increased pressure. A 50 percent decrease in breakdown strength was measured for a

temperature increase of 45°C using thin sheets (0.1 mm) without cable impregnating additives. Thicker sheets (1.0 mm) with and without additives had less than 35 percent decrease in breakdown strength.

3.3.3.4 Surface Surrounding Void. Initially the void or crack surfaces will be reasonable smooth, macroscopically, in encapsulating materials such as epoxies and polyurethanes. Microscopically, the surfaces are always rough with pits and jagged protrusions just as the surfaces of metallic electrodes are. As the void or crack is exposed to partial discharges, the surfaces will be either eroded (silicones) or treeing will take place (epoxies). The treeing tends to go toward the point of high voltage. Both treeing and high voltage will make the void bigger, increasing the number and magnitude of the discharges and eventually leading to breakdown of the dielectric.

3.3.3.5 Temperature Effects. For practical insulation materials, substantial changes in dielectric properties occur at high temperature (Figures 18 and 19). At room temperatures and low frequency, dielectric loss is low and changes slowly as temperature is increased. On further heating, the viscosity of the polymer is decreased until polar groups can move under the forces generated by the external field. At some temperature, polarization and relaxation will be in equilibrium with the applied field at all times during a cycle. In such a high-temperature regime, dielectric loss increases very rapidly with temperature. The loss-temperature curve rises continuously and the polymer at high temperatures becomes a semiconductor (Figure 21).

Significant changes in the dielectric constant also occur with changes in temperature (Figure 18), altering the effective parallel and series capacitances surrounding an enclosed void or crack. Lowering the dielectric constants lowers the impressed voltage across the void. The partial discharge initiation voltage would then rise if gas density were held constant inside the void. The density of a gas is a function of temperature and pressure. The gas density is defined as the number of molecules per cubic centimeter at pressure P. Pressure, volume, and temperature of a perfect gas are related by the equation: $PV = NRT$

where:

P = pressure in torrs or Pascals

V = volume in cubic centimeters

T = absolute temperature in degrees Kelvin

N = number of moles

R = Joules per degree Celsius per mole

This is the reason why the minimum initiation voltage varies with spacing. As the spacing is decreased, the minimum initiation voltage occurs at lower voltage at constant pressure, as shown by the Paschen-law curve (Figure 32).

The test conditions for simulating a given operating pressure and temperature can be calculated by using this relationship derived from the ideal gas law:

$$P_t = P_o \left[\frac{273 + t_t}{273 + t_o}\right] \qquad \text{(Volume being constant)}$$

where:

t_o = operating temperature in degrees Celcius

t_t = test temperature in degrees Celcius (usually room temperature)

P_o = operating pressure in Pascals

P_t = test-chamber pressure in Pascals

3.3.3.6 Impressed Voltage. Partial discharges are counted with a pulse height analyzer or similar instrument when dc measurements are conducted. The random nature of the discharges make quantitative measurements difficult, especially with capacitors for which most test apparatus is designed to evaluate a 10-pF capacitor. With a large capacitor, say 1.0 mfd., a small reading of 10-pC may represent an actual 100-pC discharge inside the capacitor void: a very damaging discharge. With transformers, circuit boards, and inductors the readings are more realistic. Kreuger (Reference 70) has shown that the ratio of charge transferred in a dielectric void to the change in charge observed in the external circuit (R_{ct}) is :

$$R_{ct} = \frac{\text{Charge transfer in void}}{\text{Charge in external pulse}} = 1 + \frac{t}{kd}$$

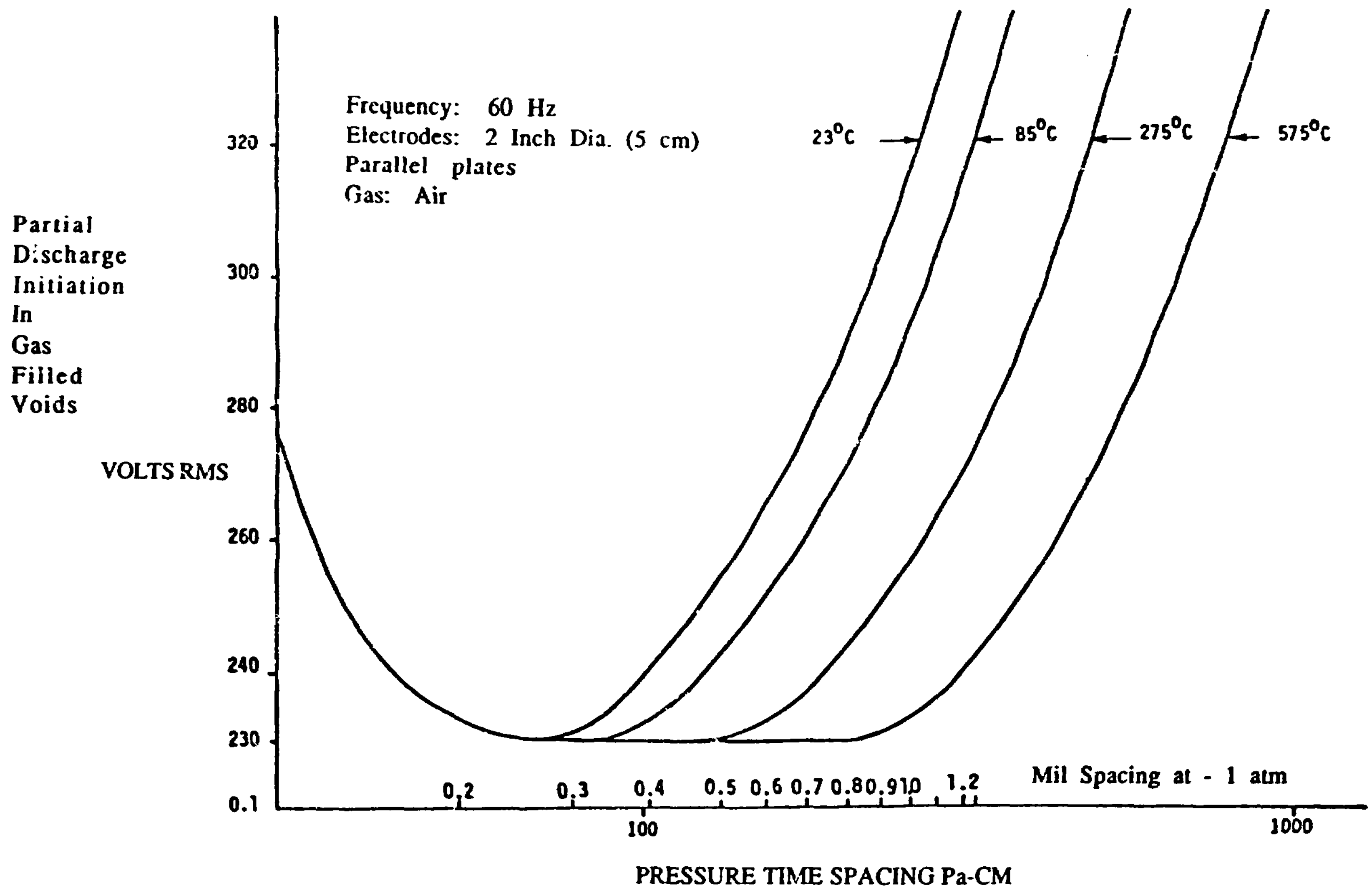


Figure 32. Pressure Times Spacing as a Function of Temperature

where:

d = thickness of the cavity

t = thickness of the dielectric

k = dielectric constant of the solid material

For example, if a void in a dielectric has these features:

$t = 0.017$

$k = 3.4$

$d = 0.001$

then:

$$R_{ct} = \left(1 + \frac{t}{kd}\right) = \left(1 + \frac{0.017}{3.4 \times 0.001}\right) = 6$$

Thus, a 10-pC reading on a corona detection instrument would represent a 60-pC discharge in the capacitor. A 60-pC discharge would cause damage to a typical capacitor and shorten its life.

Time is important when measuring partial discharges with direct voltage. Measurements by Mason (Reference 65) have shown that cavities of 2 mm diameter may take as long as 10^3 sec to discharge at a given steady-state voltage. For smaller cavities of 0.4 mm diameter, the time lag was up to 10^4 sec. In tests with epoxy resin impregnated paper at 20°C, the initiation voltage, V_i, was up to 3.5 times greater when the voltage was raised rapidly rather than with a step of 20-second duration. The time effects were small for samples tested at 60°C. Temperature is very important when measuring partial discharges.

Ionization occurs in the gas and a charge accumulates on the surfaces of the cavity, which enhances the stress in the gas during voltage rise (fall). If the voltage is raised in small steps every 20 second, the initiation voltage will be much lower than found with rapidly rising voltage.

When alternating voltage is applied to discs containing a cylindrical cavity, as in Figure 31 (upper), the inception voltage is within ±15 percent of the voltage predicted by the formula $Vi = Eo\,[d + (t - d)/\,\varepsilon_s]$ where t is the

thickness of the sample under test, including the void and ε_S depends on the relative permittivity ε_r and the geometry and orientation of the cavity. Each has the following values:

$\varepsilon_S = \varepsilon_r$ for pancake-shaped voids horizontal to the electrodes

$\varepsilon_S = 1$ for pancake-shaped voids perpendicular to the electrodes

$\varepsilon_s = \frac{3\varepsilon_r}{2 + 2\varepsilon_r}$ for a spherical-shaped void within the test sample

A rule to follow when comparing alternating voltage to direct voltage readings is to consider peak-to-peak voltage. With direct voltage all the voltage is impressed across the dielectric and void in one direction. With alternating voltage, the total voltage impressed across the dielectric and void is from the positive peak to the negative peak of the sine wave.

With 60 Hz ac voltages, the partial discharge counts increase significantly as applied voltage is raised above the imitation voltage. With ac superimposed on a dc voltage, the partial discharge pulses decrease in both magnitude and number as the ratio of dc voltage to ac voltage peak increases from 0.05 to 1.0. The loss tangent of the material also decreases significantly (Figure 33).

A generalized curve showing breakdown of air as a function of frequency at the Paschen-law minimum is shown in Figure 34 (References 71 and 72) These data indicate little change in the Paschen law breakdown minimum for frequencies between 50 Hz and 2 kHz. Indeed, the curve is nearly flat. Above 2 kHz there is a gentle lowering of the voltage breakdown from 220 volts to 170 volts at 2 MHz. There is a drastic drop of the breakdown voltage to about 50 volts between 2 MHz and 200 MHz. Above 5 GHz, the breakdown voltage rises again.

The effect of a square wave is similar to that of adding an impulse to an ac voltage. R. J. Densley (Reference 73) developed the technique of analyzing square waves. He found that the leading edge of a square wave will have the same effect as an ac voltage with an impulse at the zero voltage point on the

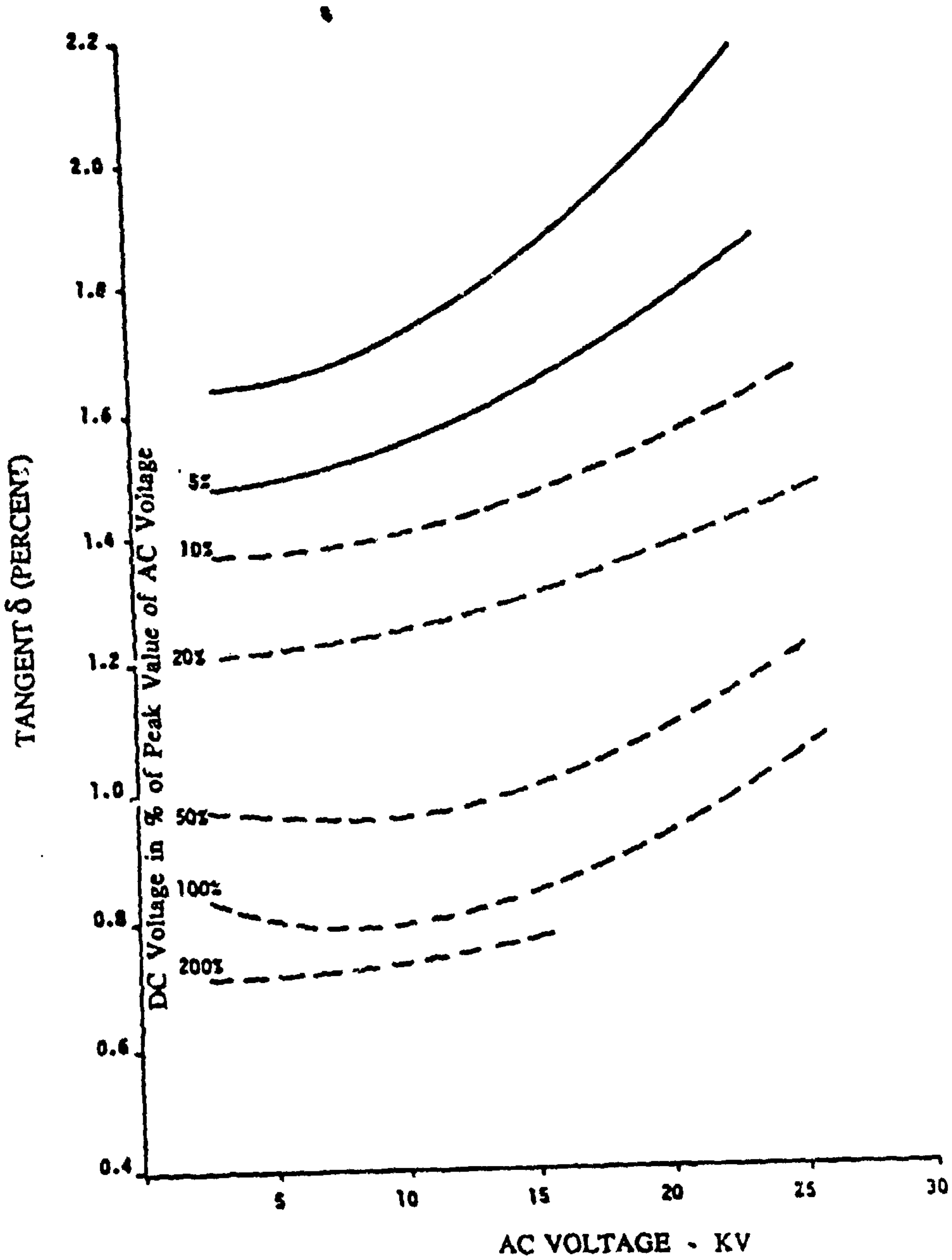


Figure 33. Dependence of Tan δ on the Voltage with Simultaneous DC Voltage. Impregnated Paper Cable Insulaton. 96.0° C, 50 Hz.

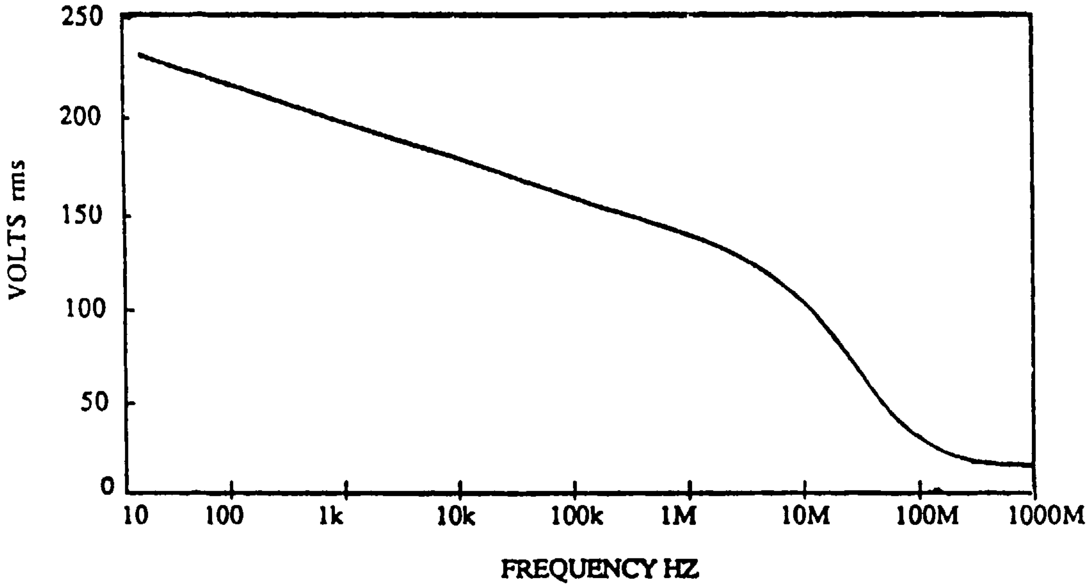


Figure 34. Lower Breakdown Voltage Results From Higher Frequency Between Thin-Film Coated Parallel Plates

sine wave. The impulse from the square wave will initiate partial discharges, which may continue throughout the waveform. Most of the discharges occur immediately after the impulse with few or none at the end of the constant voltage plateau. The number of the discharges and their duration depends on the amplitude of the square wave, the reverse stress across the void or crack after the leading edge passes, and the frequency of the square waves.

3.3.4 Surface Flashover. Current flowing across the surface of an insulator, especially when slightly wetted and containing a conductive contaminant, may produce enough heat to generate a track of carbon. This conductive path tends to reduce the capability of the insulator to hold off the voltage. With some materials, the surface erodes without producing a track. Fillers effectively reduce the tracking tendency of organic materials. Eroding materials such as acrylics do not require filler protection. Tracking can also be controlled by reducing the voltage stress on the surface by applying Petticoat insulation configurations to lengthen the surface creepage path.

New porcelain insulators may be coated with a cycloaliphatic coating containing an inorganic filler. The finished product will then be able to withstand higher voltage stress than the original porcelain. In time, surface erosion and exposure to ultraviolet radiation will degrade the epoxy-based laminate coated with cycloaliphatic epoxy to a level inferior to the porcelain. In one application having a glass-cloth epoxy-based laminate coated with cycloaliphatic epoxy the surface was stressed at a voltage of over 45-kV/cm impulse and 35 V/cm dc. However, the atmosphere was sulfur hexafluoride, and such high voltage-stress is not recommended for long-life equipment.

An experiment was performed to evaluate the flashover voltage measured between 1.9-cm-diameter washers on an uncoated glass epoxy-band laminate (Figure 35). The washer was spaced 1 to 4 cm apart. Shown in Figure 36 is the flashover voltage initiation as a function of spacing at three frequencies. The impulse and steady-state flashover voltage stress is shown for the same configuration in Table 14.

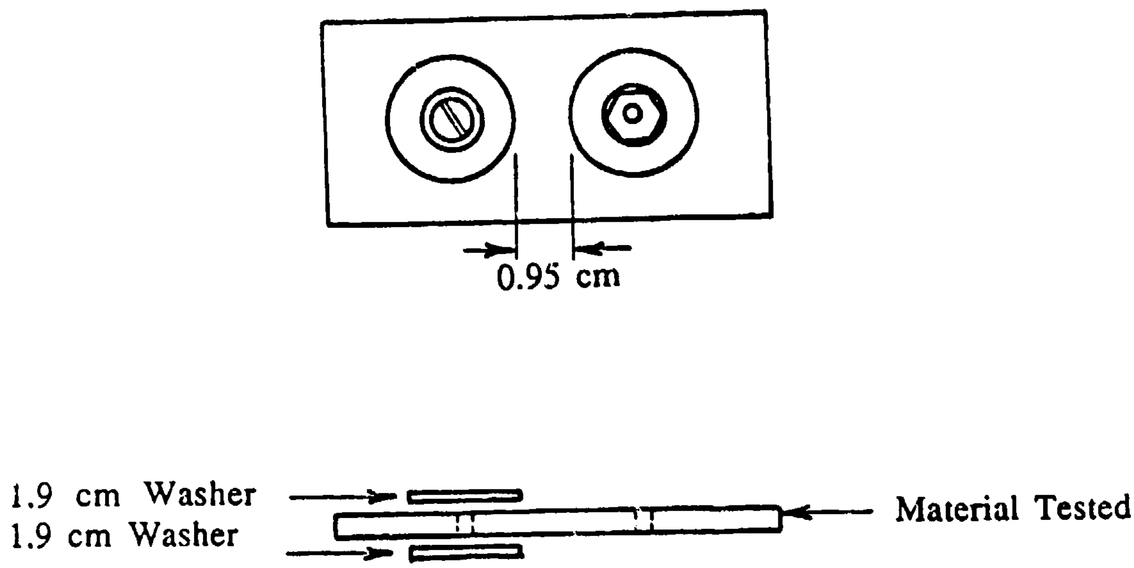


Figure 35. Flashover Fixture

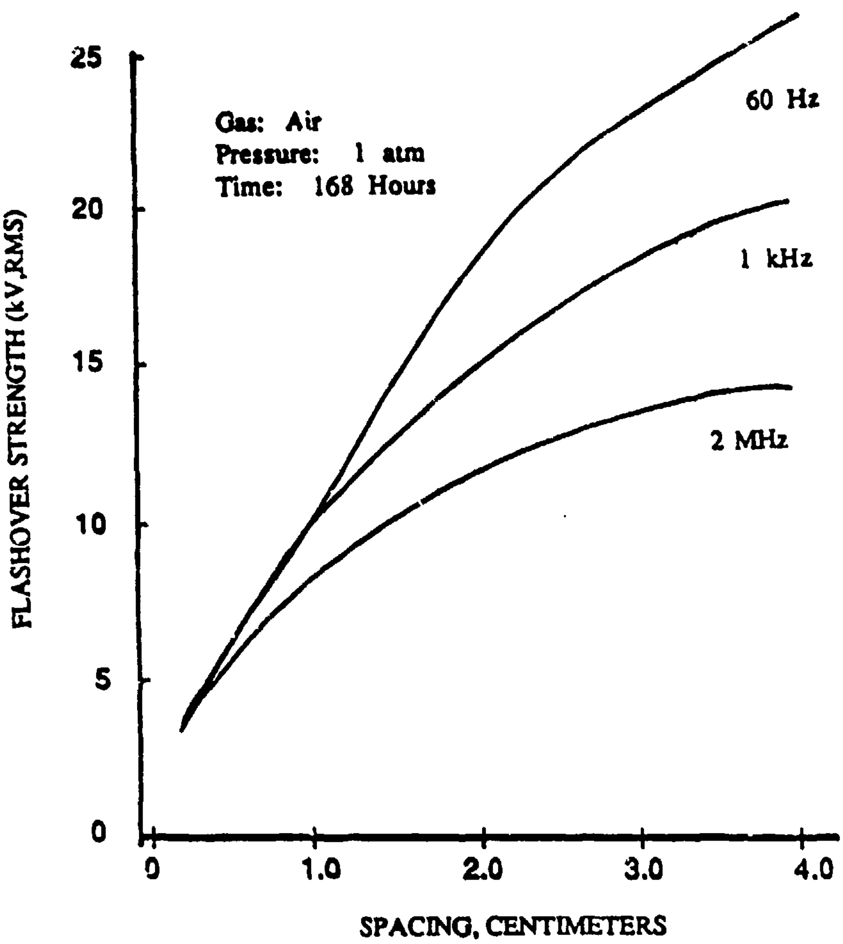


Figure 36. Effect of Spacing on the Initial Values of Strength for the Fixture Shown in Figure 35

3.3.4.1 Temperature Effect on Flashover Strength. It is both interesting and useful to determine the relationship between flashover strength at 25°C and that which would prevail at some other temperature, T. For gaseous breakdown in a uniform field, this relationship involves the ratio of the gas densities at the two temperatures. To test this relationship, it is only necessary to multiply the 25°C value by the factor (25 + 273)/(T + 273), which is the inverse ratio of the absolute temperatures involved. This ratio is part of the well-known air density correction factor, which is commonly used in spark-gap measurements over a considerable range of density and gap spacing. The broken lines in Figure 37 show the values obtained when this factor is applied to 25°C flashover values.

TABLE 14

COMPARISON OF STEADY-STATE AND IMPULSE FLASHOVER STRESS, V/CM (PEAK) FOR GLASS EPOXY-BOND LAMINATES

Test (1 Minute Duration)	Average Flashover Strength For 1-CM Spacing
	kv
Steady-State	
60 Hz	14.1
dc positive	14.9
dc negative	16.7
Pulse	
positive	17.1
negative	18.6

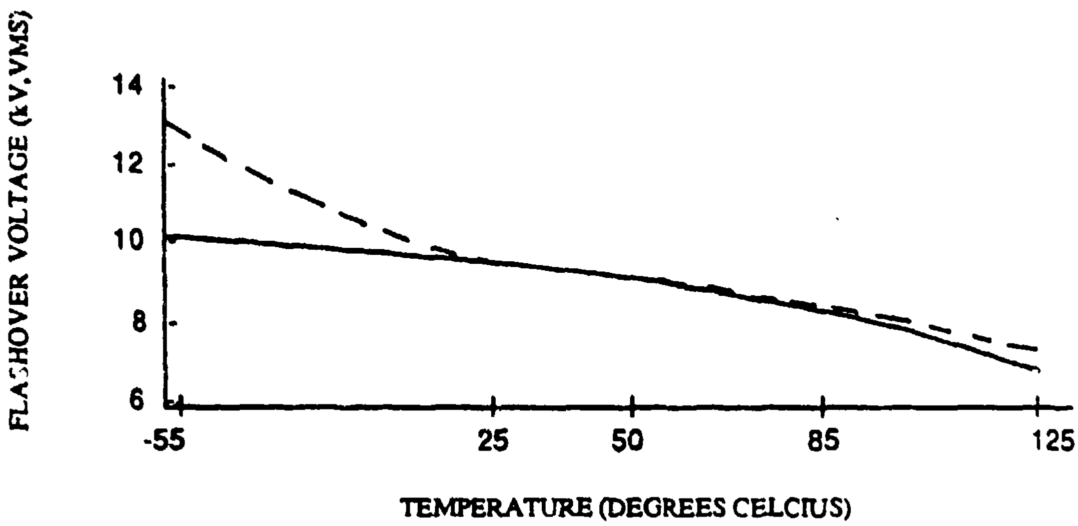


Figure 37. Effect of Temperature on 60 Hz Flashover Stress

3.3.4.2 Frequency Effects. All materials have lower flashover strength at higher frequencies. The example given in Figure 38 illustrates the magnitude of the change.

High dielectric constant materials have much lower resistance to surface voltage creep than the low dielectric constant materials. Figure 39 illustrates the advantage in selecting insulation with the correct dielectric constant. The "breakdown factor" in the illustration represents the results of many measurements, showing how a decreasing flashover voltage can be expected across the dielectric when insulation with progressively higher dielectric constants are tested.

A bibliography on surface flashover, surface creepage, and tracking on or within solid insulation is cited in References 74 through 92.

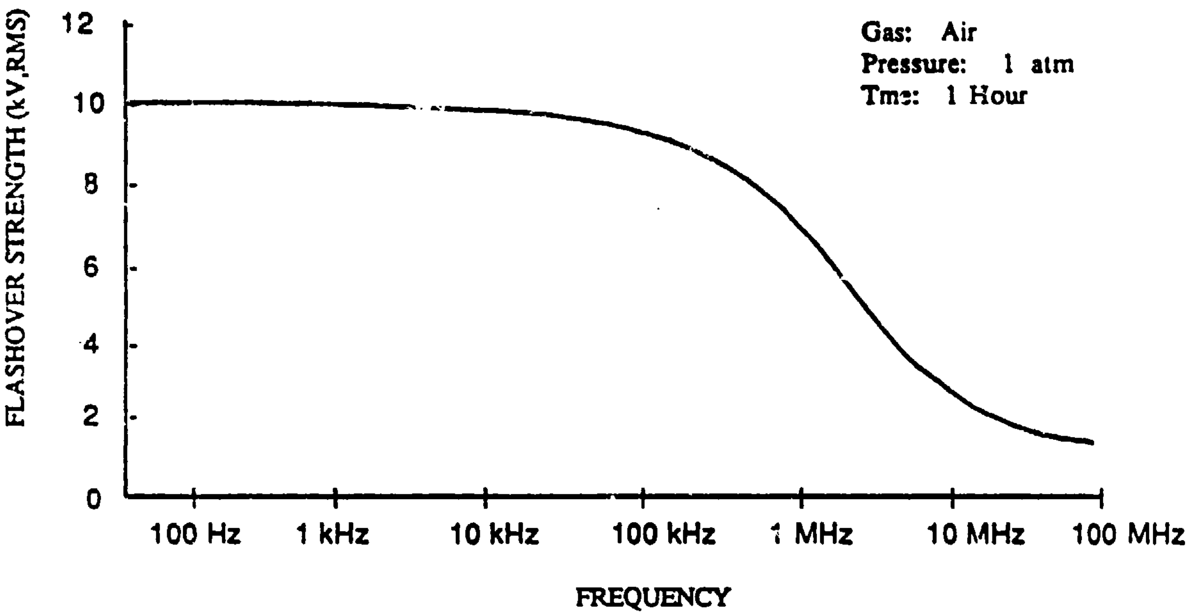


Figure 38. Effect of Frequency on Flashover Strength for Configuration Shown in Figure 35

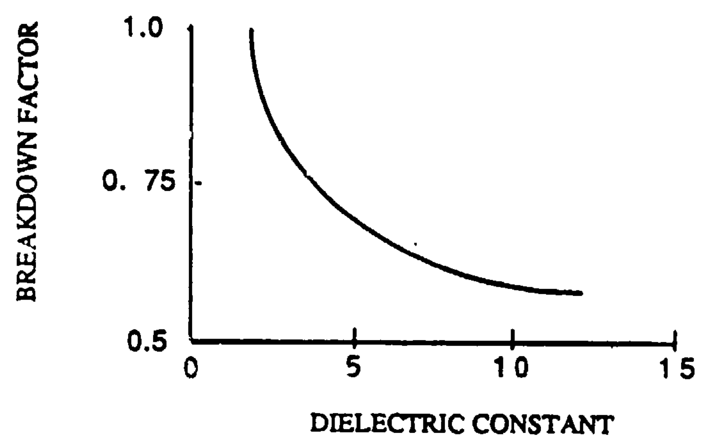


Figure 39. Variation of Flashover Voltage with Changing Insulation Dielectric Constant

SECTION IV
ENVIRONMENT

When an electrical system is planned for a new or future aerospace plane, environment must be considered as an important design requirement. Unpressurized electrical systems and modules for airplanes operating to 60,000-foot altitudes may use conventional design practices for voltages to 208 volts rms. Only a few airplanes in today's inventory require special design criteria for low-pressure corona or partial discharges at altitudes above 60,000 feet. Future aerospace planes and shuttle-type vehicles may be required to use spacecraft design techniques for high-altitude environmental conditions. This section only uses the term "spacecraft" to refer to an aerospace plane or orbital vehicle.

4.1 Pressure. Many aircraft are designed or will be designed to operate in near space or space where the low pressure (less than 10^{-4} N/m^2) makes the theoretical dielectric strength of the volume of gas greater than $5x10^5$ V/cm, a value 16 times the dielectric strength of dry air at sea level. This is because there are few carriers and the mean free path exceeds the gap length between closely spaced electrodes. But in space or near space, the electronic modules and circuits slowly outgas during ascent to altitude and for the remainder of the mission. For instance, during ascent to altitude, the vehicle's external pressure may decrease rapidly from Earth sea-level pressure ($1.013x10^5$ N/m^2) to values approaching $1x10^{-5}$ N/m^2. This pressure change takes only a few minutes, but the pressure next to the outer surface and inside the aerospace vehicle remains at a higher level until it once again returns to the Earth's surface, because of the outgassing of various materials. For the rest of this discussion the assumption is that the vehicle will go to orbit altitude and remain there for several hours or days.

4.1.1 Internal Gas Pressure. During ascent, gas escapes rapidly from the vehicle interior for the first 30 km altitude while continuum gas flows. This is because of the slow outgassing, through small orifices, tubes, and cracks, of gases entrapped in electrical and thermal insulations and structural materials.

If the vehicle has no outgassing products, the flow of gas can be calculated by the Clausing equation which is used to estimate the flow of gas from chamber to chamber in a multiple-chamber vacuum system.

$$C = 3.638\ A_k\ (T/m)^{1/2}$$

where:

C = flow conductance for the orifices in cubic centimeters per second

A_k = area of the k orifices in square centimeters

T = internal temperature in degrees Kelvin

m = mass of the gas molecule in grams

Scialdone (Reference 93) calculated and measured compartment and equipment outgassing rates. He shows that the depressurization time constant, t, which is the time for the pressure to decrease to 36 percent of its initial pressure, is V/C, where V is the volume in cubic centimeters and the conductance C is:

$$C = 1/4\ \bar{v}\ A_k$$

$$\bar{v} = (8kT/\pi m)^{1/2}$$

where:

$\bar{v}$ = molecular flow speed in centimeters per second

k = Boltzman constant.

Gases such as air and nitrogen have a time constant of about 0.4 second when bled through a 1-cm^2 opening in a 10-cm-radius steel sphere. NASA experience (Reference 94) has shown that a 0.1 time constant ensures adequate outgassing around most high voltage circuits.

These equations work well with known outgassing port sizes, spacecraft volumes, and non-gassing parts. However, most vehicles have thermally insulating coatings, semisolid structure, fibrous insulation, electrically insulated parts, semishielded and electromagnetically shielded boxes, and

boxes within modules. In addition, compressed gases for orbit keeping are stored on the vehicle and periodically released. With these many gas and outgassing sources, it is often better to qualify the design by testing the completely assembled vehicle in a thermal vacuum chamber than to measure the real internal and external spacecraft pressures and the outgassing rate.

4.1.2 Outgassing Through Insulation. An experiment was designed to show the relationship between the outgassing rate of an electronic component under a thermally insulating blanket versus that component in the outside atmosphere. In this laboratory experiment, a thermal blanket with 100 layers of super-insulation was placed across the center of a vacuum chamber Gas flowed through the interstitial spaces in the insulation. During the first 15 minutes of pump-down, the pressure in the chamber dropped from sea level to 10 N/m^2, with the gauge on the thermally insulated side of the chamber following the pump pressure within 5 percent, as shown in Figure 40. As the pump pressure dropped further, the pressure at the insulated side of the chamber decreased very slowly.

In one space vehicle, the outgassing area was measured to be about 1 cm^2/L volume, the value recommended for adequate outgassing when high voltage experiments or equipment are on board. The resulting pressures reported (References 95 and 96) are summarized in Figure 41.

Cuddihy and Meacanin (Reference 97) in measuring the outgassing rates of polyurethane foam used for electrical and electronic insulation, found that the calculated value based on the reported permeation constant of the measured value agreed within a factor of 2. The diffusion coefficient (D) for a foam is calculated with the equation:

$$D = P_e \left(\frac{RT}{m}\right) \frac{P_0}{P} \left[\frac{1}{(1-P/P_0)} 1/3 + 1 + (1 + P/P_0)^{1/3}\right]$$

where

D = the diffusion coefficient in cubic centimeters per second

P = the foam density in grams per cubic centimeters

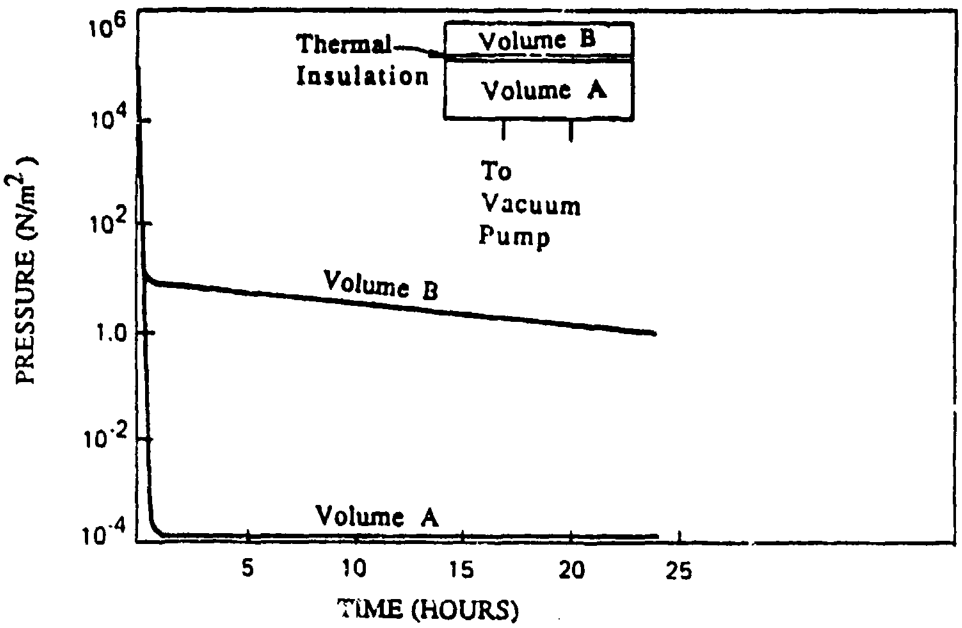


Figure 40. Effects of Thermal Insulation on Outgassing Rate

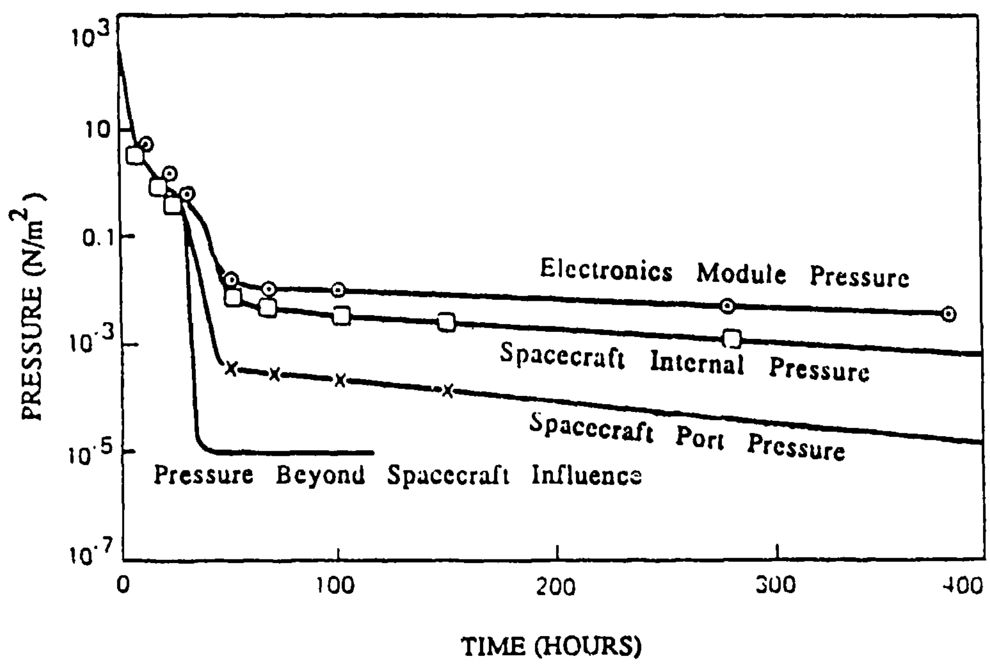


Figure 41. Gas Pressure Inside the Apollo Telescope Mount

P_e = the permeation constant in millimeters per second per square centimeter torr

P_0 = the density of the bulk polymer in grams per cubic centimeter

R = the gas constant

T = internal temperature in degrees Kelvin

m = mass of the gas molecules in grams

They also found that for sufficiently long outgassing time, the weight loss of the gas, when plotted as a function of the thickness of the solid (A), eventually becomes linear with the slope of $(\pi/2A)^2$ D.

These data show that the vehicle internal pressure is significantly greater than the external pressure for several days after orbit insertion. Furthermore, outgassing products within a high voltage module may keep the pressures much too high for safe, reliable operation of high voltage circuits, making it advisable to delay their TURN ON. Likewise, the outgassing products of the vehicle and reaction control propellants increase the pressure in the vicinity of the vehicle. For very high power, high voltage equipment it may become necessary to package in pressurized gas or oil to prevent corona and/or voltage breakdown due to slow outgassing and pressure.

4.2 Particulates. Many future high power space missions will require large spacecraft to support the onboard loads (Reference 98). Some of these spacecraft will require kilowatts to megawatts of electrical power. Even though the amount of cosmic dust flux is very small in low Earth orbit to geosynchronous orbits, the effects of cosmic dust on large spacecraft are significant enough to produce problems with high voltage systems. A number of predictions on the effects of space environment on large spacecraft have been based on experimental experience gathered from small satellites (References 99, 100 and 101). However, little attention has been paid to the effect of particulate debris on the power systems of these spacecraft, probably because there is no evidence that particulate space debris has caused problems for low voltage small satellites. A brief preliminary analysis of the expected

problems that the power system of a large spacecraft might experience as a result of contamination by particulate debris has been made (Reference 102).

4.2.1 Sources of Particulate Debris. Spacecraft are impacted by particulate debris from the following three sources:

a. Earth environment. Debris from the Earth's environment are mostly dust and sand particulates and particulates from rocket exhaust (Reference 103). This contamination is easily minimized by implementing existing techniques for high standards and control; therefore, the Earth's environmental effects are not considered in this analysis.

b. Spacecraft environment. In addition to the degradation caused by the impact of debris, outgassing of some of the materials from the spacecraft generates more debris. Possible sources for such debris are the power generation system, electric insulating materials, thermal blankets, propulsion engines, and the main structure. In addition, spacecraft ion thrusters emit ions that contaminate the space plasma.

c. Space environment. It should be remembered that outer space is not an absolute vacuum. There are residues of gases that form the space plasma, and also particulate debris that are of extraterrestrial origin. The term "cosmic dust" refers to particulate debris with masses up to ≤ 1.0g; i.e., micrometeoroids and small meteoroids. Extensive studies have been conducted on cosmic dust (e.g., References 104 through 106).

4.2.2 Aerospace Vehicle Size. The design of a spacecraft, particularly of its electrical power system, and the purpose of its mission, play an important role in its susceptibility to debris contamination. Large spacecraft with large electrical power systems in the order of hundreds of kilowatts are more subject to problems caused by particle debris than are smaller spacecraft because of the following characteristics, which are inherent in the design and the function of large spacecraft:

- The high voltages and high currents of interconnectors, cables, and buslines generate strong electric and magnetic fields that strongly influence particulate debris-spacecraft electromagnetic interaction.
- The large areas of dielectric materials in the high-power solar array structure produce strong electric fields because of surface charging and differential charging. This tends to collect particulate debris.
- Use of low-density materials in the spacecraft structure yields some outgassing and fragmentation products.
- The requirement for long life (i.e., 10 to 20 years) will lead to cumulative effects of particulate debris impacts. These characteristics are barely evident in the design of small spacecraft; therefore, their effects are not significant.

The importance of the role played by these characteristics depends, however, on the amount of particulate debris. The following section, discusses how much debris can be expected and what the subsequent effects will be.

4.2.3. Debris Ejection and Its Effects. The experimental work of Gault and Heitowit (Reference 107) showed that an aluminum projectile striking basalt surfaces with a velocity of 6.25 km/s^{-1} inducted ejecta of mass that were approximately 370 times the mass of the projectile. Dohnanyi (Reference 108) and Marcus (Reference 103) have indicated, however, that a large range of experimental results on ejecta generated from impacts on rocks are approximated by $M_e = 5\ V^2 M_p k^2$, where M_e and M_p are the masses of ejecta (kilograms) and projectile, respectively; V km^{-1}/s is the velocity of impacting particles relative to the targets; and k is a normalization constant 1.0 km^{-1}/s. Thus, for a velocity of 6.25 km^{-1}/s, this equation would yield almost half the amount suggested by Gault and Heitowit, which further suggests that this equation presents a conservative estimate of ejecta generated by cosmic dust impacting the spacecraft. Using the previous information on cosmic dust speed and flux in the Dohnanyi and Marcus formula leads to an estimate of expected ejected mass from the solar panel. The ejected mass lies in the range

$5.65 \times 10^{-4} \leq M_e \leq 10^{-2} g\ m^{-2}\ day^{-1}\ (2\pi sr)^{-1}$. This mass removal will cause a significant perturbation to the spacecraft orbit over the long period of operation and should be considered in the orbital analyses of the spacecraft. The produced ejecta are subjected to the electric and the magnetic fields that surround the spacecraft. Hence, debris, whether from space or from the spacecraft, will be swept (and collected at selected regions) by the fields of unshielded high voltage and high current conductors. When the debris particles have entered the field of the conductor (Figure 42), they will become charged and polarized to form a seta (hairlike) growth on the conductors. Some of these charged particles will form bridges or "strings of pearls" between high voltage and low voltage or ground planes (Figure 43). The field stress at the ends of the seta is very high, so any plasma in that region can and will initiate an arc between the conductor and the ground plane or another conductor. This causes power losses and changes in physical characteristics. Other problems resulting from particulate debris contamination are:

- Short circuiting of electrical elements
- Arcing and surface damages over the main structure
- Arcing on the main bus lines to communication antennas, which causes current irregularity and produces intolerable noise in addition to physical damage
- Degradation of paints and surface finishing
- Excessive wear and binding of movable parts because of contamination of lubricants, seals, and sliding surfaces

4.2.4 Settling Debris. Particulate debris that are settled on or that are suspended near the spacecraft will be charged up such that, at equilibrium conditions, the potential at their surfaces will equal that of the nearest surface of the spacecraft. This leads to high potential at the particulate debris surface, especially if it is in the shadow or near a dielectric. Charges build up on particulate surfaces until they discharge or until they break down because of the electrostatic pressure. This phenomenon of breakdown may be described by the semiempirical relation (Reference 107):

$$F = 8.85 \times 10^{-7}\ \phi^2 / r^2$$

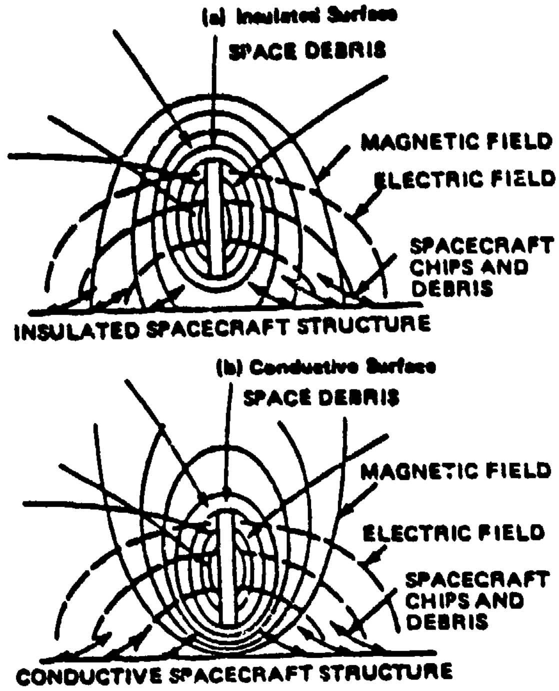


Figure 42. The Configuration of Electric and Magnetic Fields Will Influence the Trajectories and Hence the Collection of Debris.

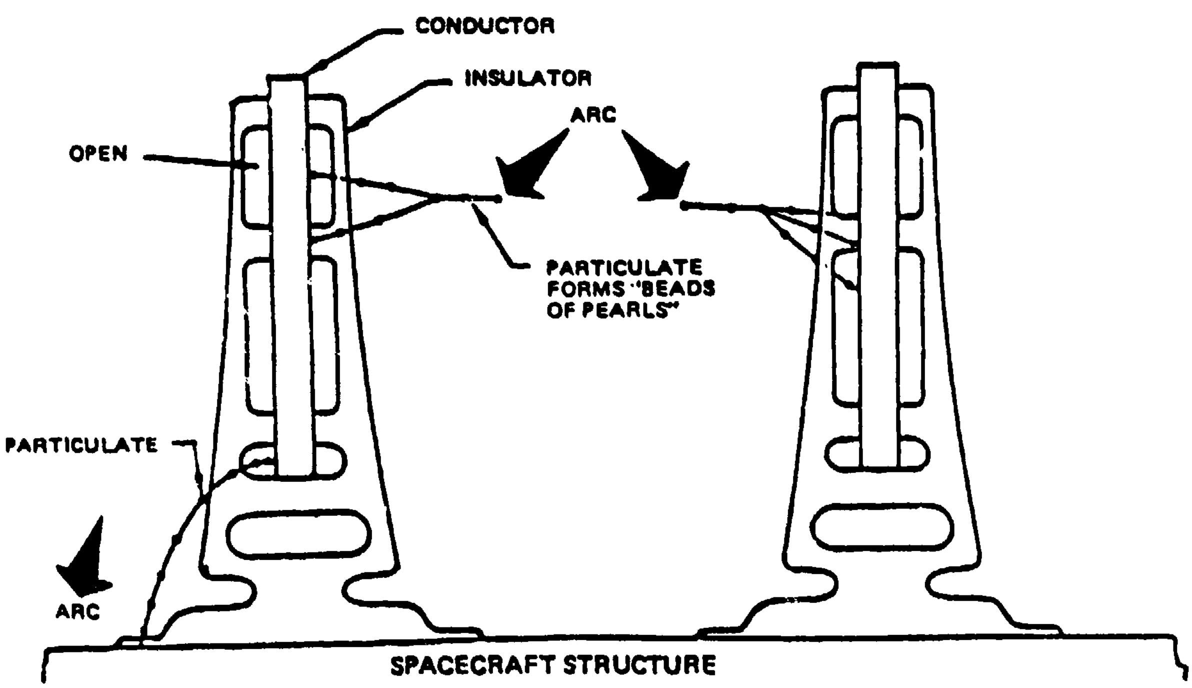


Figure 43. Arcs Caused by Particulate Bridge Between Conductors

where F is electrostatic stress on a tensile of a particulate in dyne/square centimeters, Φ is the particulate surface potential in volts, and r is the particulate radius in centimeters.

If F exceeds the particulate's tensile strength, the particulate will break apart, yielding smaller particulates. Some particulates tend to migrate to specific localized regions on the spacecraft because of the electromagnetic interaction, where setas are formed that eventually lead to shorting and/or arcing. Quantitative estimates of the produced debris are unavailable. Experimental investigation is required to determine the amount of particulates produced as a result of the breakdown of different particulate materials (i.e., different composition, shape, size, etc.) that are subjected to a wide range of surface charging.

4.2.5 Controlling Incident Particulate Debris. To control damage induced by particulate debris, stronger but lighter materials must be developed to withstand the impact of energetic particulates. Although many materials developed recently satisfy this criterion, there are still limited successes (e.g., solar panels are still susceptible to mechanical damage by debris). This indicates the limitation of this approach and suggests the need for developing a complementary approach so that a satisfactory solution can be achieved. One method is to slow down, deflect, and/or to prevent particulate debris from impinging on the spacecraft. This may be achieved by using the electromagnetic fields of the electric currents of the spacecraft. The electric charge of the particulate debris (and its magnetic moment if it possesses one) interacts with the electromagnetic fields and, thus, it is possible to control its motion relative to the spacecraft as shown in Figure 44.

4.2.6 Controlling the Potential. As previously mentioned, energetic debris produces plasma bursts on impacting the spacecraft. These plasma, produced by the ion thrusters, solar wind, the ambient plasma, and the photoelectric effect continuously change the electrostatic potential of the spacecraft through uncontrolled charging and discharging mechanisms. Obviously, to maximize spacecraft performance, one has to limit the potential on its surfaces

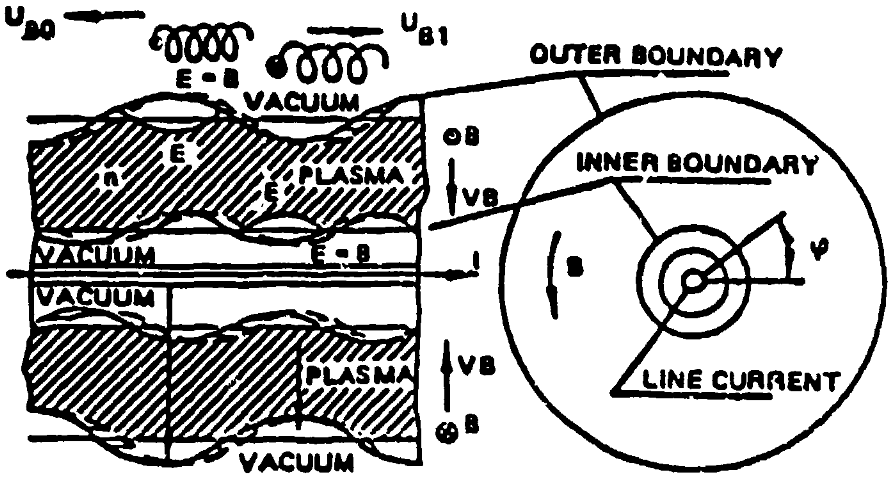


Figure 44. Cylidrical Shell of Plasma Confined in the Magnetic Field from an Axial Line Current

to acceptable values. Several interesting techniques have been developed for controlling the potential of small spacecraft. These techniques are based on the emission of charged particles using an active or inactive potential control system. As a demonstration for active control systems (References 110 through 113) two techniques have been used: the hot wire filament electron emitter for the ATS-5 and the plasma bridge neutralizer for the ATS-6. Both systems share the concept of releasing electrons from the charged spacecraft. The plasma neutralizer of the ATS-6, however, has another advantage; ions from the discharged plasma in the neutralizer are attached to the neighboring insulating surfaces, discharging them. For inactive systems, Grard, et al. (Reference 114) and Grard (Reference 115) investigated the possibility of using an electron field emitter. Its operation is based on charge dissipation in the ambient environment which primarily depends on the potential difference between the spacecraft and the environment This potential difference forces electrons to leave sharp pointed filaments at the end of a conducting boom attached to the spacecraft. No power source is required to activate this mechanism, but the length of the boom has to be several times the dimensions of the spacecraft to minimize the influence of the induced charge (in the spacecraft) on electron emission. In these techniques, the interaction between the released electrons and the ambient environment is not fully understood. This adds another obstacle in addition to that for scaling in attempting to implement these techniques for large spacecraft. Of the available analyses on large spacecraft, very few tackled the concepts for reducing plasma impacts. These are the previously mentioned analyses of Parker and Oran and of Miller et al. (References 116 and 117), which are based on shielding rather than bleeding or neutralizing the parasitic charges. Excessive charges flow through this conducting system to designated sites. By properly coupling these sites, one may use the excessive charges to perform specific tasks in addition to controlling the static potentials on the spacecraft surface. The selection of either type of conducting system for a design recommendation will be based on detailed trade studies that include performance, weight, cost, degradation, and power output at the end of design life

4.3 Environmental Interactions With Space Power Systems. When an aerospace plane operates in orbit, it interacts with the naturally occurring space plasma. The low-temperature ionospheric plasma density distribution is shown in Figure 45 (Reference 118) as a function of altitude for an equatorial orbit. The plasma density varies with the 11-year sun-spot cycle and this figure provides maximum and minimum densities. Both maximum and minimum peak near 150 NM reach a plateau near 1100 NM, and fall off drastically above 6600 NM.

The initiation voltage breakdown in a plasma environment is shown in Figure 46. These data are based on laboratory tests (References 119, 120 and 121) and flight tests. Breakdown voltage is defined as the minimum voltage that can generate a discharge in a select environment. A cross plot of Figures 45 and 46 is shown in Figure 47, which provides the initiation breakdown voltage versus altitude for maximum and minimum densities. It is important to recognize that the data of Figure 47 are for exposed (non-insulated) electrical elements in the natural environment of an equatorial orbit. Induced environments and other orbits must be considered as applicable for specific missions.

The orbital environment can interact with the onboard systems so as to significantly affect both the operation and lifetime of these systems. The relative motion of the vehicle and the plasma causes vehicle sheaths and wakes to be formed by the electric fields and the charge differences between the vehicle and the plasma. It is possible that, due to such phenomena, the vehicle could be charged to high voltage levels that could result in an electrical breakdown or discharge between the vehicle and the plasma environment. These discharges or short circuits can affect the operating systems adversly.

4.4 Surface Charging. Environmental-spacecraft interactions may be characterized by the two following broad categories:

Vehicle Passive: The environment itself interacts with "neutral" spacecraft surfaces, both conducting and

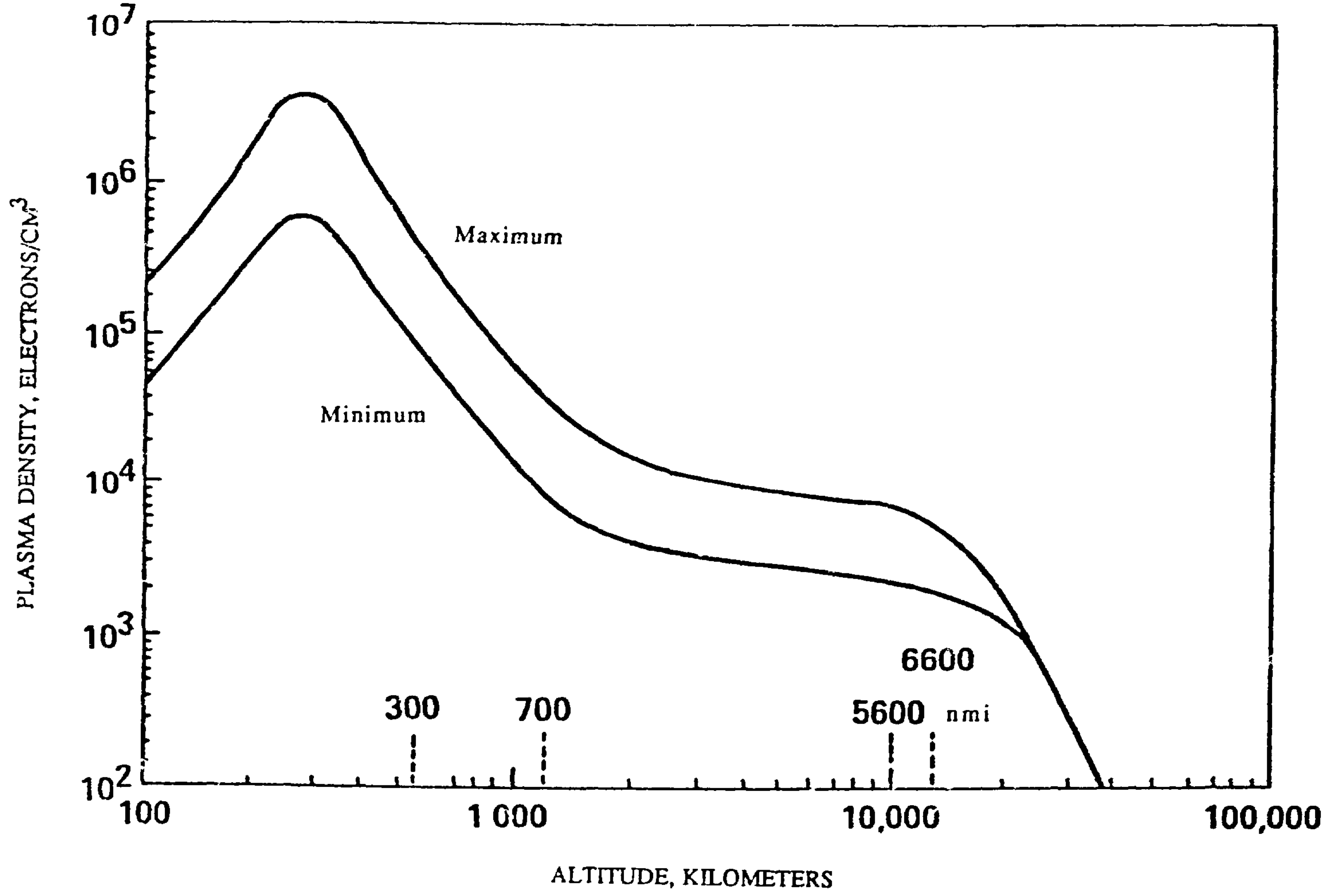


Figure 45. Plasma Density Versus Altitude

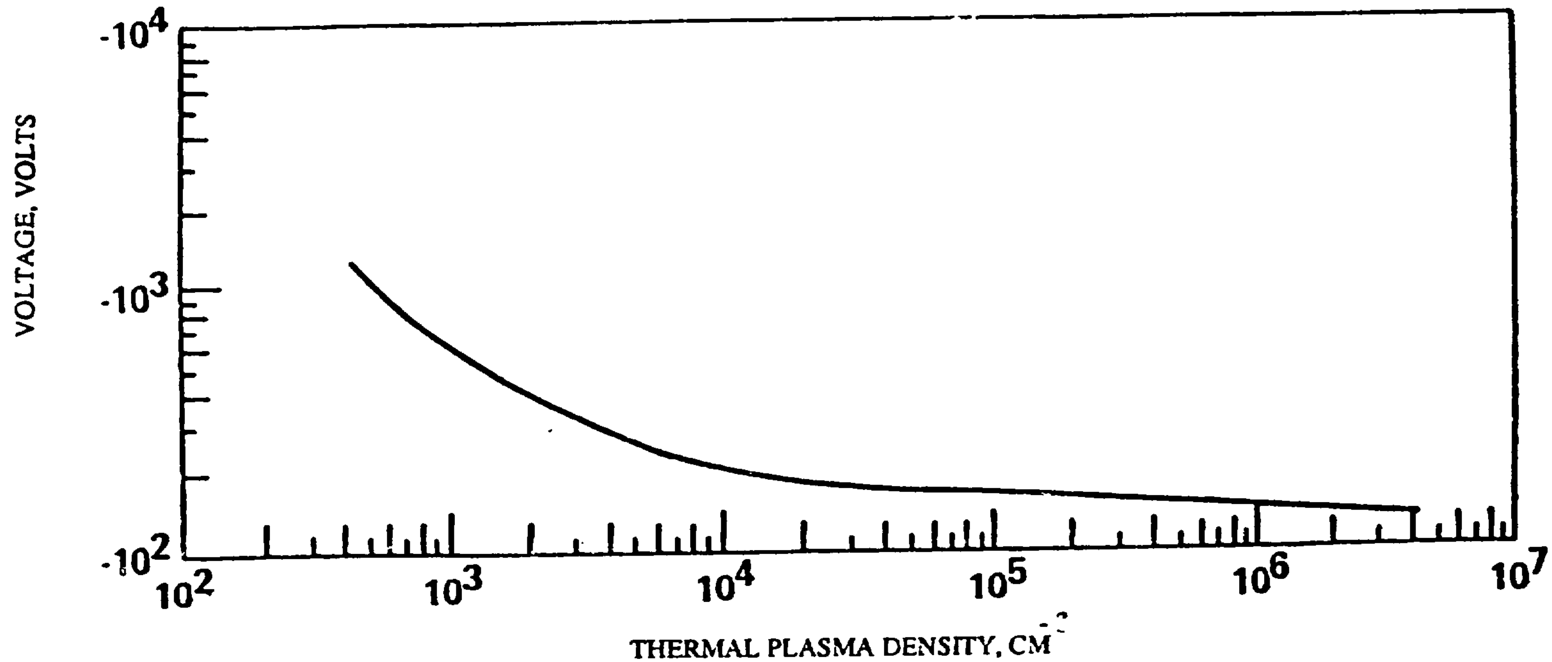


Figure 46. Voltage Threshold for Breakdown

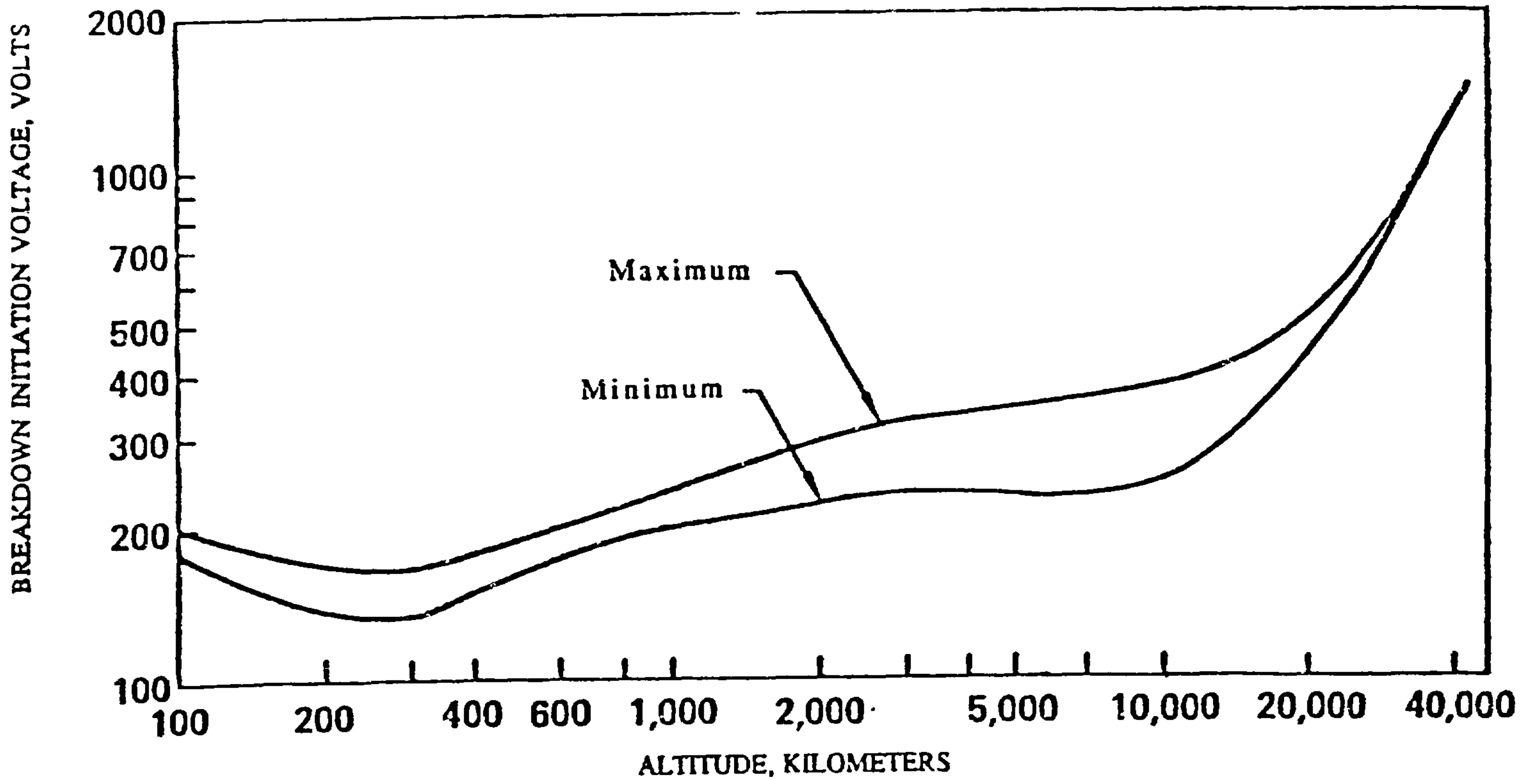


Figure 47. Effects of Plasma on Exposed Bare Conductors

nonconducting, including reactions with the elements of the space environment that degrade materials.

Vehicle Active: The operation of the vehicle of an onboard system, by reason of high voltage exposed elements or charge accumulation due to the operation of vehicle systems, is a major cause of the "interactive" phenomena.

The primary vehicle passive interaction is that of charging. Differential charge buildup between various satellite elements can occur, which can result in arcing between neighboring surfaces. This arcing can affect component and system operation or cause significant damage to onboard components. Table 15 shows a list of potential hazards due to arcing.

Differential charging on vehicle surfaces can result from at least two distinct processes: surface charge buildup and charge deposition in dielectrics. Dielectrics or isolated conducting surfaces can build up potentials, over long periods of time, that are well in excess of the breakdown potential threshold for the various materials. Certain insulating materials are also known to store charge in the bulk of the dielectric material, which can be released by an external perturbation such as X-radiation. This will initiate an internal discharge and "punch through" the insulator, resulting in an electrical system fault.

Important factors in vehicle charging may be related to long-term accumulation and alteration of surface contamination layers. Such accumulations and alterations can have a significant effect on both the mechanical and electrical properties of the affected materials. Large aerospace planes, especially aerospace planes in high orbits, are particularly susceptible to the effects of charging and high energy debris. Cosmic dust may strike the vehicle at velocities greater than 10 km/s. Impact-evolved, spalled material and dust can become charged and collect on high voltage insulators, enhancing flashover.

TABLE 15

POTENTIAL SPACECRAFT HAZARDS

Electromagnetic Interference

- Upsetting of logic circuits, e.g., false commands
- False telemetry signals
- Alteration of electrical component parameters
- Damage or burnout of electrical components

Thermal Control Degradation

- Burnout of ground straps
- Deposition of burnout materials on surfaces
- Alteration of surface absorption and emittance properties
- Insulator contamination and/or tracking

Optical Sensor Degradation

- False optical signals due to arc discharge flashes
- Deposition of arc materials on optical surfaces

Mechanical Effects

- Coulomb forces due to electrostatic charging
- Coulomb forces due to electrostatic arc discharges (quick release of steady-state forces)
- Mechanical distortions due to long-term changes

The vehicle active environment interactions are those caused or affected by the vehicle itself by virtue or presence of generated voltages or other interference fields. This class of interactions will be increasingly significant for future high power systems. As power systems increase in the direction of high power, the losses and weight penalties associated with low voltage systems will drive the power systems to higher levels. Because of the high power levels at which these systems will operate, equipment interactions with potentially high magnetic fields (due to high currents) and/or high electrostatic fields (due to high voltages) will have to be dealt with.

4.4.1 Discharge Due To Improper Bonding. Another place where the effect of vehicle charging can be detrimental is where the conducting sections of the vehicle are not bonded together; for example, a rocket vehicle is charged triboelectrically on the forward surfaces and discharged through corona from the skirt at the aft end. If the forward section is not electrically connected to the aft section, charge acquired on the forward section cannot flow to the aft section unless the potential difference between the sections becomes large enough for a spark discharge to occur. The electrical isolation could occur as a result of improper electrical bonding at the interface of two sections. These spark discharges can be quite energetic because the capacitance between the sections may be several thousand picofarads and the sparkover voltage may be several kilovolts. Furthermore, the spark discharge will seek the easiest electrical path between the sections. If some electrical wiring is routed across this gap, it is possible that the spark will travel through a shorter gap from the front section to the wiring, through the wiring, and then through another short spark gap to the aft section. This, of course, would put a tremendous noise pulse on any data line. Also, there is the possibility that these spark discharges could fire electro-explosive devices. Proper bonding between sections of the spacecraft is mandatory.

4.4.2 Streamers From Insulators. Vehicle charging can also be detrimental when the vehicle skin is composed of dielectric or of dielectric-coated sections that can become charged triboelectrically from passage through ice crystals or other particulate matter. In contrast with the metal skin, the charge cannot flow away from the point where it is deposited. Charge thus

accumulates on the surface until the electric field along the surface is large enough to support a streamer discharge over the dielectric surface to a metal structure nearby. However, if the dielectric strength of the insulator is exceeded before the streamer occurs, the charge is relieved by a spark discharge that punctures the dielectric and travels to an underlying conductor. Streamer discharges, like spark discharges, seek the easiest path to the vehicle structure.

4.4.3 Windshields. Because windshields are made of an insulating material, the same sort of effects occur with them as with other dielectric materials. Streamer discharge from windshields is a source of RF noise.

4.4.4 Coating Insulators and Windshields. It has been found that a high-resistance conductive coating over the dielectric surface is quite effective in eliminating streamer noise. The conductive coating drains away the charge as rapidly as it arrives and prevents the electrostatic potential buildup that produces the streamer discharges. The coatings (Reference 122) used for non-transparent dielectrics are usually opaque and have a surface conductivity on the order of 1 Megohm.

Most windshields are made of either glass or acrylic plastics. Glass has a lower surface resistance, 10^{12} ohms, than the acrylics, (10^{16} ohms). This is attributed to the somewhat open silica network in glass which allows hydration. It has been shown that a surface resistance of 10^{8} ohms is probably sufficient to bleed off accumulating charge.

The principal coating presently used for glass outer panels is stanous-oxide, which can be fused into the glass exterior surface to sufficient depth that erosion should not seriously reduce the conductivity of the external surface coating during the life of the windshield.

4.4.5 Discharge Effects on Electro-Explosive Devices. Electro-explosive devices in the rocket can be set off by corona discharges. Unbonded sections present a real danger because of the intensity of the spark and because the

spark may discharge through an electro-explosive device. Streamer discharges can also be energetic enough to ignite one of these devices.

4.5 System Design Criteria. The design parameter discussed in Section III will be used to develop conceptual system design trades for an aerospace plane using the following parameters, which influence electrical insulation application with respect to voltage, environment, and configuration:

- Gas Pressure, 100 kPa to 10^{-3} kPa
- Temperature, -55°C + 295°C maximum ambient
- Spacings, normal electronic hardware equipment
- Gases, LN_2, N_2, LO_2, 0_2, Air, CO_2, NH_3, and H_2
- Pressurization as required

Power systems voltages proposed for aerospace planes are shown in Table 16.

These requirements and system voltages require special consideration with respect to electrical insulation, partial discharge, and corona. Techniques to prevent system disturbances and foreshortened life will be discussed in the following section. Although different voltages and frequencies exist inside a power supply module the same design techniques apply for voltages less than 750 volts, peak.

4.5.1 Gas Density Relationship. The corona or breakdown voltage of a gas as a function of gas density and spacing is different for each gas and gas mixture and is affected by the electrode material and configuration. The breakdown voltage is always the same for a given gas and gas density, regardless of what combination of pressure and temperature produce that density for electrode spacings between 0.5 and 25 mm and temperatures below 500°C.

The breakdown voltage may be related to temperature and altitude by using the U.S. Standard Atmosphere, which gives the air-density factor as a function of altitude. Thus, it is possible to simulate any altitude and temperature in a room-temperature chamber containing gas at an appropriate pressure. However, this simulated environment ignores higher order effects

TABLE 16

SYSTEM VOLTAGES

Voltage	Conductor
270 Vdc	2
650 Vdc	2
115 V, 400 Hz	4
230 V, 400 Hz	4
115 V, 1600 Hz	4
440 V, 20 kHz	2

from chemical and thermal dielectric deterioration, which would occur at a temperature other than room temperature.

The conditions for simulating a given operating altitude and temperature can be calculated by using this relationship derived from the ideal gas law:

$$P_t = P_0 \left(\frac{273 + t_t}{273 + t_o}\right) \quad \text{Constant Volume}$$

where:

t_0 = operating temperature in degrees Celsius

t_t = test temperature in degrees Celsius (usually room temperature)

P_0 = operating pressure in torr

P_t = test-chamber pressure in torr

Figure 48 shows the corona initiation voltage (CIV), as a function of gas pressure and temperature for round nichrome wires having a fixed spacing. For each constant temperature curve shown, the CIV follows Paschen's law in the low-pressure region, decreasing to a minimum voltage at a predictable pressure, followed by an increase in CIV as the pressure is further reduced. There is some variation in the minimum CIV at temperatures between 500° to $1100^{\circ}C$, but little or no change from 23° to $500^{\circ}C$.

4.5.2 Helium Leak Test. Helium used for leak detection, if entrapped, reduces the breakdown voltage. If mechanical or electrical stressing should cause the insulation to crack internally, the crack can fill with helium rather than nitrogen or other pressurizing gas. When the helium partial pressure is between 13.3 $N/m^2 (1 \times 10^{-1}$ torr) and 2.66x103 N/m^2 (20 torr), it can ionize, generating partial discharges at very low voltage within the void, and possibly resulting in insulation failure as shown in Figure 49.

4.5.3 Insulated Conductors. Insulated conductor data are developed for terrestrial applications under normal sea-level operations. When the same insulated conductors are subjected to very high altitudes, the data may not

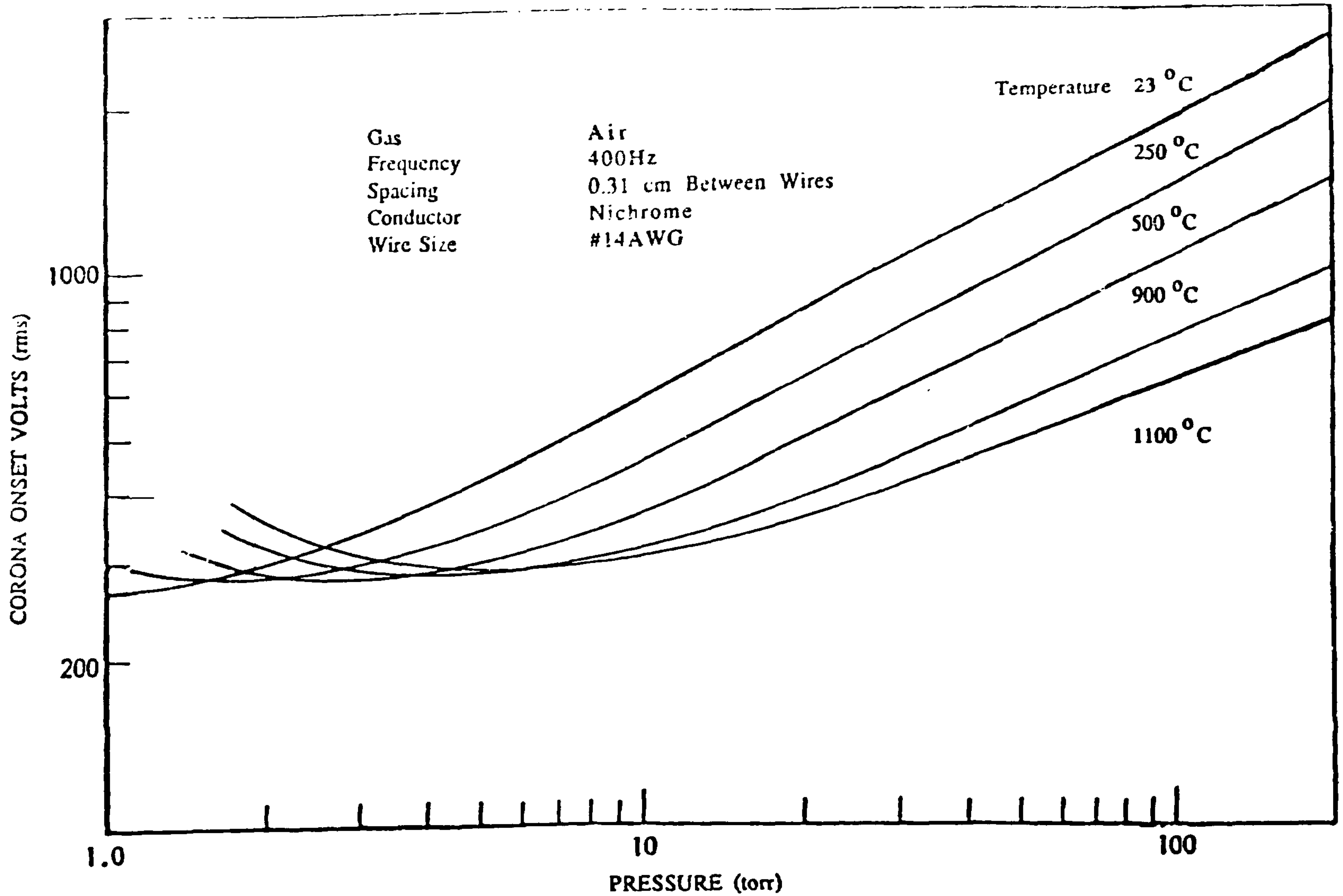


Figure 48. Corona Initiation Voltage as a Function of Temperature and Pressure for Parallel Wires in a Heated Chamber

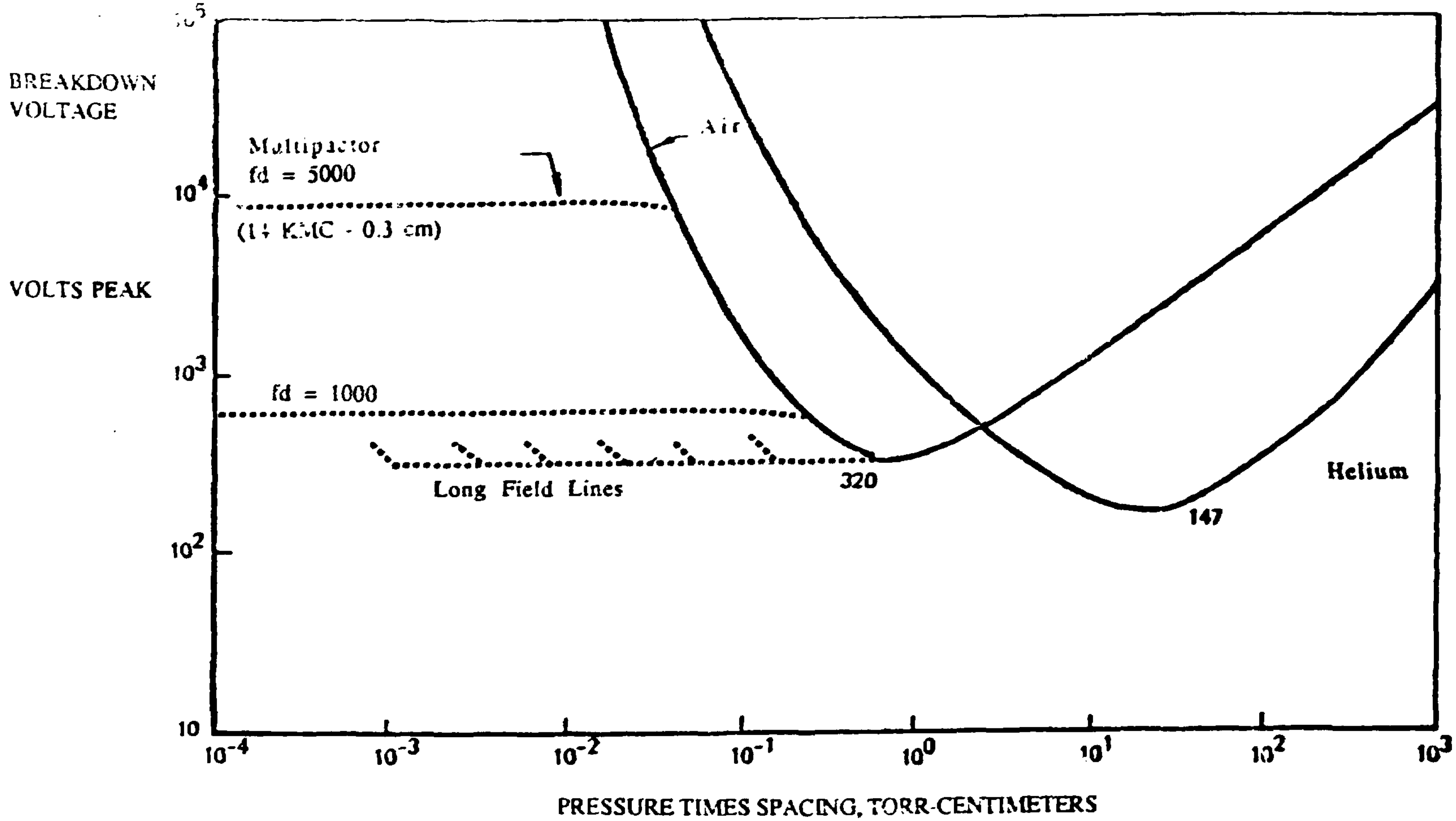


Figure 49. Theoretical Voltage Breakdown for Parallel Plate Configurations

apply because the gas between the conductors or between a conductor insulation and ground may go into corona, heat the insulation, and eventually cause the insulation to fail. When designing wiring systems, the voltage between components and wires must include the long field paths as well as the short paths. Note the case for parallel insulated wires in Figure 50. In this example, the spacing between the wire insulation and ground plane is very small or negligible, whereas the space between the upper surface of the insulation and ground is very long compared to the insulation thickness. As gas pressure decreases, partial discharges are first formed in the narrow space between the insulation and ground (Curve A) Figure 51. At that gas density most of the voltage drop is across the insulation rather than in the air gap. As pressure is further decreased, the optimum mean free path for voltage breakdown becomes longer and the voltage gradient in the insulation decreases as does the voltage, decreasing the breakdown potential between the conductors. This condition continues until the insulation contributes little to the voltage drop (Curve B). The insulation effectiveness as a function of pressure is shown in Figure 51. All the time a glow discharge exists on the surface of the insulated conductor, the conductor is being degraded and will soon become carbonized, if an organic, and an arcover will follow.

Insulated conductors in flat wire configurations are used in many low voltage applications. They can be used at higher voltages, provided the pressure-spacing criteria are observed. For flat wires the Paschen-law curve for adjacent conductors in a cable have a U-shape, as shown in Figure 52. It must be remembered when designing with flat conductors that the end conductors have almost the same pressure-spacing characteristic as round insulated conductors.

For most designs, in an unpressurized environment the pressure reduces to about 1 to 10 Pa, a pressure sufficient for operation at the minimum of the Paschen-law curve for most insulated and uninsulated conductors. For this critical region the variation in partial discharge or breakdown can be represented for the various fields lengths encountered as shown by the "bath tub" effect in Figure 53, which shows that insulation has little effect on the initiation of partial discharges after 20 to 30 minutes in space.

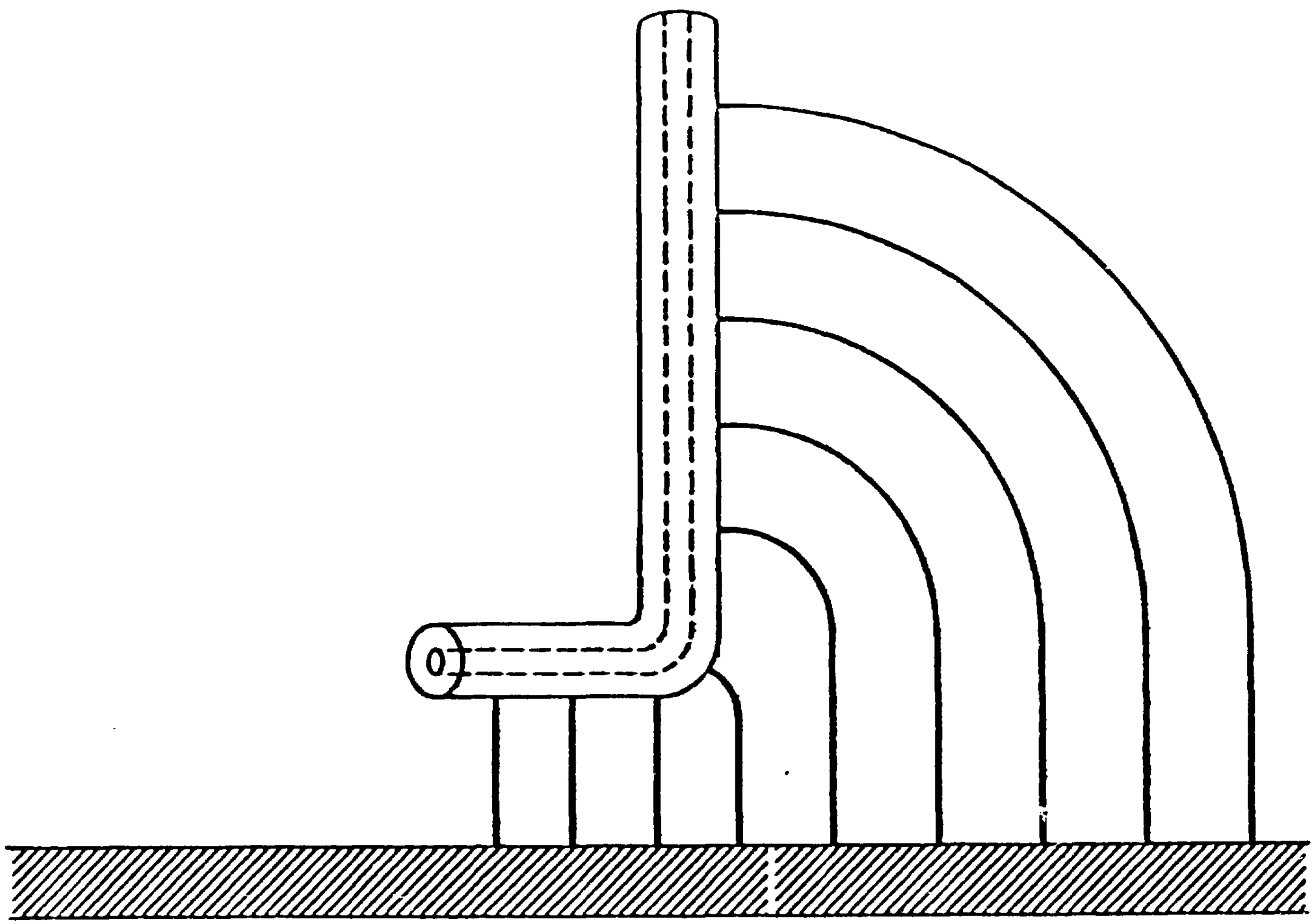


Figure 50. Electric Field Between an Insulated Conductor and Ground Plane

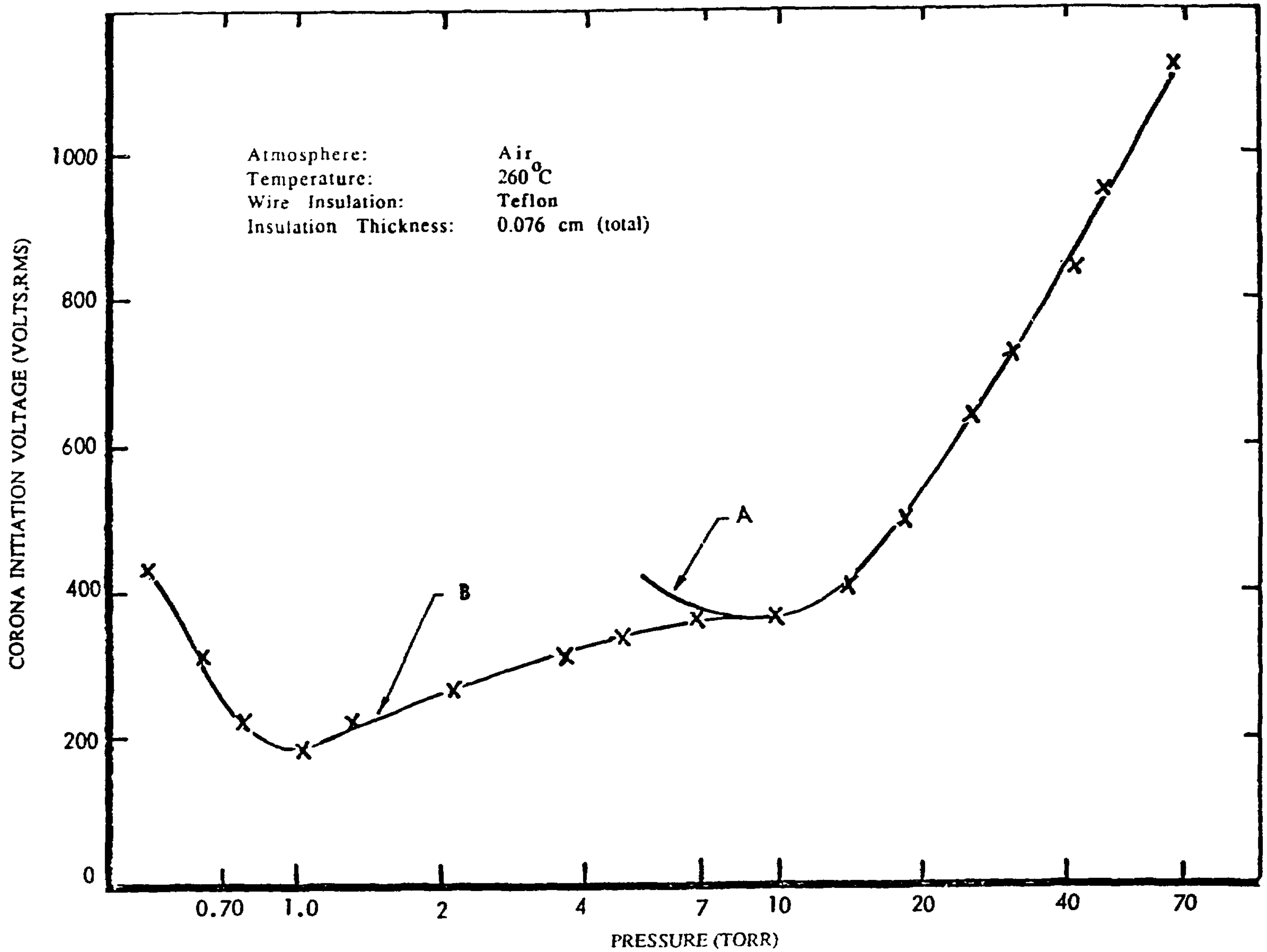


Figure 51. Corona Initiation Voltage of Teflon Insulated Twisted Wire Pairs

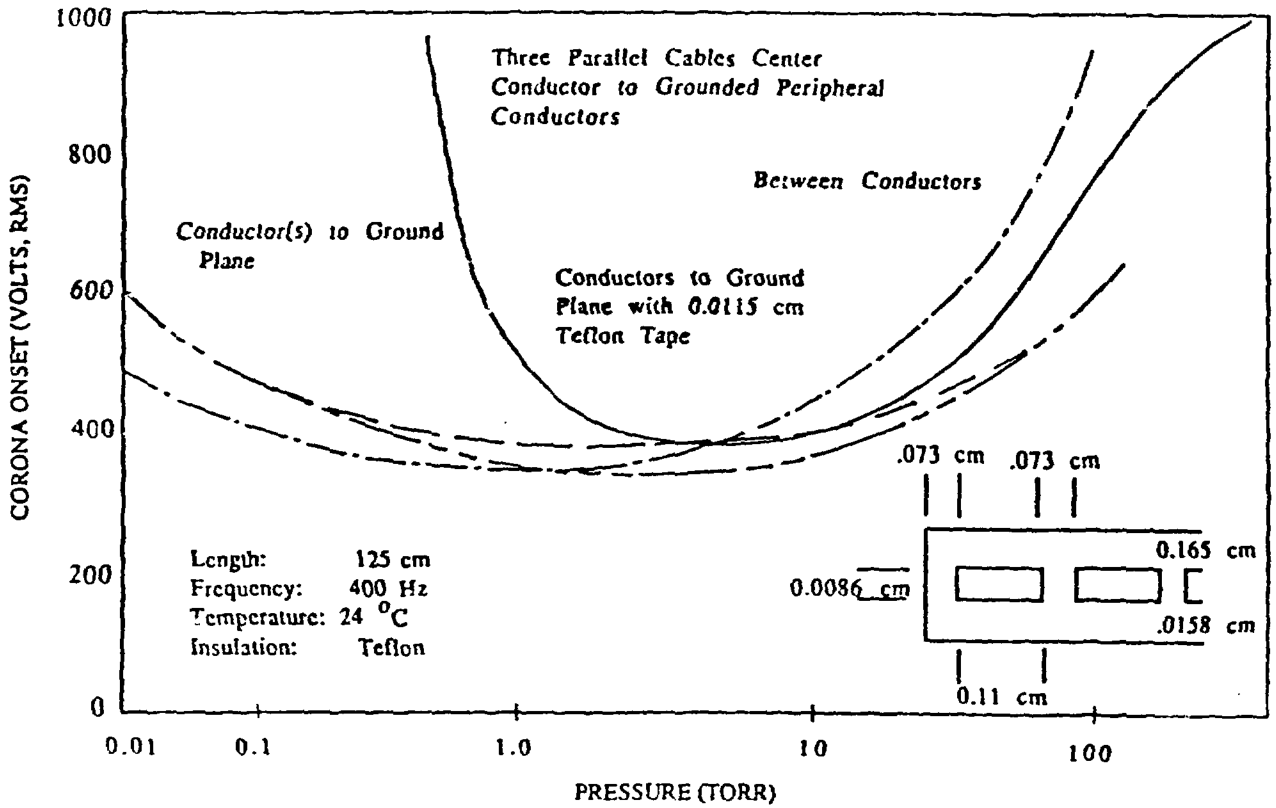


Figure 52. CIV of Teflon Insulated Flat Conductor Cable

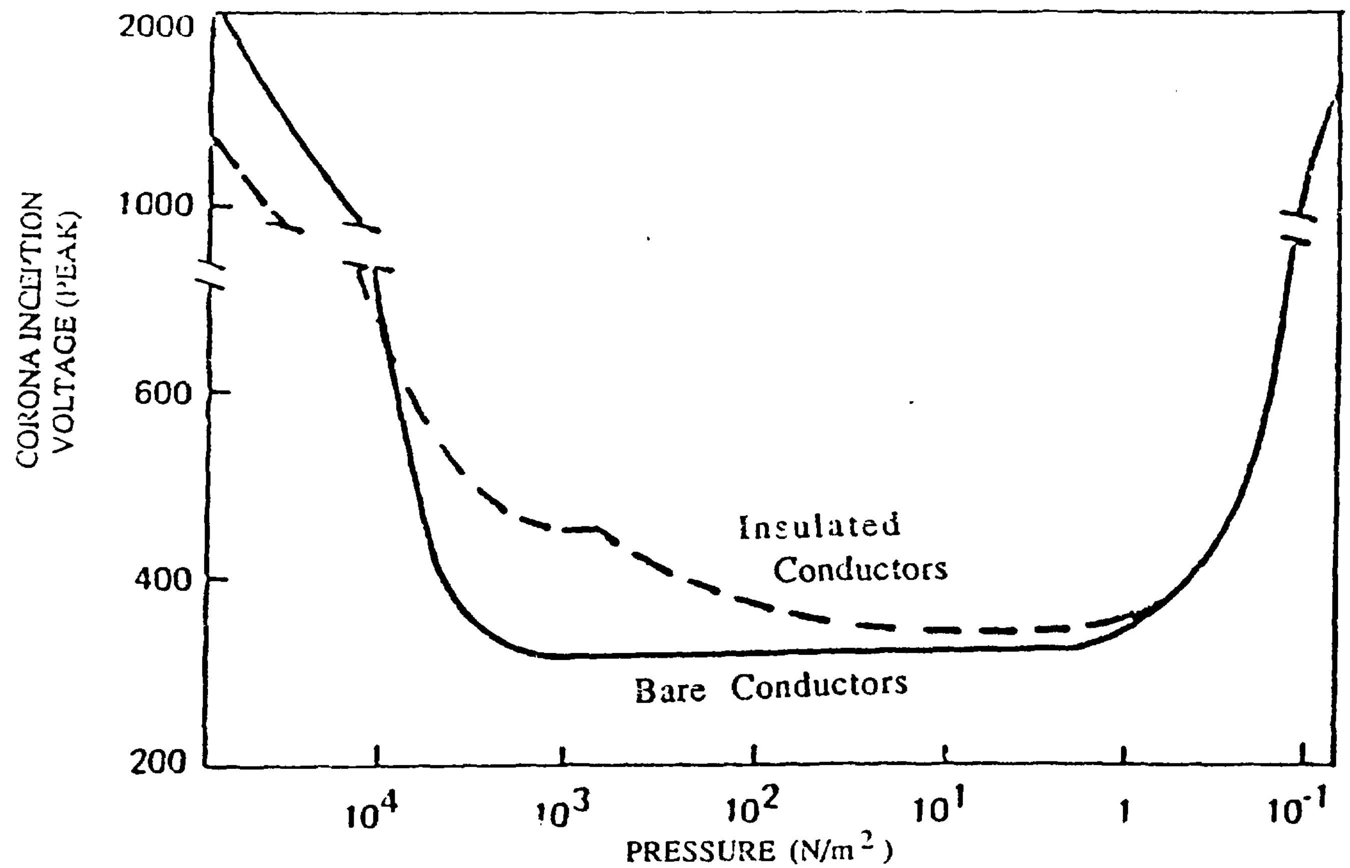


Figure 53. Critical Pressure Region for High Voltage Equipment Failure

4.5.4 System Voltage. A 115 volt ac system operates without glows, corona, or partial discharges in gaseous atmospheres of air, N_2, O_2, He, and their mixtures at all altitudes from Earth's surface and space.

Transients on a 115 volt ac system that exceed the peak voltages shown in Table 17 at the critical pressure spacings result in momentary glows or sparks. The glow or spark quenches when the voltage returns to its normal operating value.

The insulation system will not be damaged if the transient voltages exceed the breakdown limit unless they are repeated cyclically. The prospect of sustained arc is remote because the arc is started and quenched in a few microseconds. There will be enough energy in point to ground, or rod-type configuration to ground, to create very high temperatures for a few microseconds; again it would not be sustained and there is no danger of fire unless either a very flammable material, such as a hydrogen-rich ether, or an alcohol atmosphere is present. The ignition probability should be evaluated by people experienced in explosive atmospheres. Explosive atmospheres, as a rule, require a voltage above 325 volts, peak, before a spark can ignite.

a. 230 volt, 3-phase, 400-Hz. Bare 230 volt, 3-phase, 400-Hz lines are surrounded by corona or glow discharges at the critical pressure spacing altitudes. This altitude range could be from 70,000 ft to over 250,000 ft considering the slow outgassing of the vehicle. The discharges could be present during boost and for over 20 minutes. The time with discharges greatly decrease during re-entry because of the rapid pressurization.

By reducing the voltage to 200 volts, 3-phase, 400-Hz partial discharges will only occur during transients and over voltages that exceed 325 volts, peak in air. Pure gases such as hydrogen and helium would continue to experience low voltage breakdown. Nitrogen must be very pure to have a breakdown lower than that of air. A 0.1 percent contamination will destroy the low voltage electrical properties of nitrogen. Hydrogen-gas-filled compartments will require special protection for 200 volt to 300 volt dc systems.

TABLE 17

CRITICAL PRESSURE-SPACING

Voltages volts	Gas	Critical Pressure-Spacing Torr-cm
190	Helium	3 - 10
327	Air	0.2 - 1.2
265	Nitrogen	0.2 - 1.2
292	Hydrogen	0.2 - 1.2

b. 270 volt dc systems. A 270 volt dc system will not experience corona and glow discharges between bare and thinly coated electrodes in air. Electrical transients exceeding 320 volts peak in air or contaminated nitrogen will experience partial discharges, glow, and corona in the critical pressure-spacing region. Helium and Hydrogen rich atmospheres must be protected against corona, glow, and partial discharges. Hydrogen atmospheres will be able to ignite with the outgassing products of the insulating materials in the vicinity of the discharge unless properly protected by encapsulation, shielding, or pressurization.

c. High voltage systems. Power systems of 650 volt dc or 440 volt, 1-phase, 20,000 Hz require pressurized and/or sealed wiring and components. Wiring can be made corona and partial discharge free by using coaxial power lines instead of the usual two-conductor system. Breakouts, terminations, and protective devices are all very costly. The connectors must be corona free; that is, the conductor pin cannot have an air pocket surrounding the pin as in most Military standard connectors. All relays, switches, disconnects, and connected components should be either pressurized or solidly potted. Either way, the cost may be prohibitive. Termination conditioning may cost upwards of 1/2 to 1 man-hour each when the time to apply insulation, inspect, and test is considered. The voltage parametric considerations for aerospace planes are shown in Table 18.

TABLE 18

VOLTAGE PARAMETRIC DATA

PARAMETER	GASEOUS ATMOSPHERE: AIR/N_2-Air	Hydrogen	Helium	Oxygen/Carbon Dioxide
Minimum Breakdown Voltage Bare Electrodes				
AC Volts rms	230	206	134	300
DC Volts peak	327	292	190	425
Minimum Pressure Region				
Contacts and terminals	20 torr to 0.025 torr	10 torr to 0.02 torr	100 torr to 0.1 torr	3 torr to 0.025 torr
Insulated conductors (twisted)	10 torr to 0.025 torr	5 torr to 0.20 torr	100 torr to 5.0 torr	
Wires in shielded coax-not extruded	10 torr to 1.000 torr			
Coaxial cables with connectors (Mil-spec)	10 torr to 1.000 torr		100 torr to 10 torr	
Circuit breakers-contacts	5 torr to 0.050 torr			
System Voltage				
Normal Design - No Special Protection				
115 V 400 Hz 3 phase	X	X	(Protect for transients (over 180 peak; pressuri- (zation on insulation)	X
115 V 1600 Hz 3 phase	X	X		X
270 V DC	*All wiring and bare contacts must be insulated with at least 10 mils insulation *Glow discharges will exist during transients	*All conductors shielded *All components potted and pressurized	*All conductors shielded *All components potted and pressurized	X
230 V 400 Hz 3 phase	*All 3 phase wiring and bare contacts pressurized or shielded *Single phase to neutral may be treated as 115 V systems	*Same as for air	*No exceptions for single phase lines *All conductors shielded *All components potted or pressurized	*Same as 115 V ac systems
650 V DC	*All lines in coaxial configuration for all gases *All components pressurized or potted			
440 V 20 kHz 1 phase				

SECTION V
CONFIGURATION AND DESIGN DATA

Electrical component and mounting configurations are critical to a high voltage, high-density, high-power packaging design. Form, fit, and function requirements demand that electronic packaging, and materials design engineers analyze each configuration. To develop a high-performance, highvoltage electronic design, the design engineering group must consider the following facets of the design: electrically compatible electronic circuitry, good thermal control and heat dissipation, long life, and high reliability. Most design groups understand electronic design compatibility and thermal control, and, with good breadboards and components, the design can be made operational. Packaging for long life and high mean time between failures (MTBF) is usually calculated by specialists who have excellent knowledge of parts behavior with respect to electronic fields, thermal control, and mechanical integrity. For high voltage equipment, more emphasis must be placed on components, field stresses, and materials selection and application.

5.1 Field Stress Calculations. To select and design insulation for electrical equipment properly, it is often essential to make plots of the field distribution. Several techniques are possible, including:

- Analytic solution
- Conformal mapping techniques
- Finite-difference computer programs
- Simulated charge computer programs
- Resistance--network analogs
- Conducting--paper analogs
- Curvalinear hand plotting techniques

For the electronic field problems encountered in the dielectric design of transformers and electric machines, the resistance paper analog provides quick, reliable results and is preferred by many designers. Its versatility

makes it easy for the designer to quickly prepare a field plot and directly interpret the results.

These field plotting techniques are used to determine the maximum stress value in the configuration for both operating and test voltages. From the breakdown field E_S for the insulating medium, the breakdown voltage V_S can be approximately calculated from the relationship (References 123, 124, and 125)

$$V_S = \eta \, g E_S$$

Here g is the electrode separation and is the utilization factor, defined as the ratio of average to maximum gradient in the gap. In practice, for the breakdown voltage calculation, η is numerically equal to the required voltage derating, because it is equal to the ratio of the field stress between parallel plates and the maximum field at the smaller electrode of a nonuniform configuration with identical spacing. For the breakdown voltage calculation, E_S is usually taken as the breakdown field in the uniform field case.

For simple applications in the most frequently used configurations, plots of the utilization factors as a function of electrode spacing are shown in Figure 54 for several electrode geometries. The utilization factor, which provides a way to quickly estimate the maximum field stress of a configuration, can also be used to estimate the minimum electrode radius for a given spacing when the electrical stress capability of the dielectric is known. The utilization factor is numerically equal to the required voltage derating of a configuration. In equation form

$$\eta = \frac{E}{E_m} < 1$$

where

E = average voltage stress between two electrodes spaced a unit apart in kilovolts per millimeter

E_m = maximum voltage stress at the surface

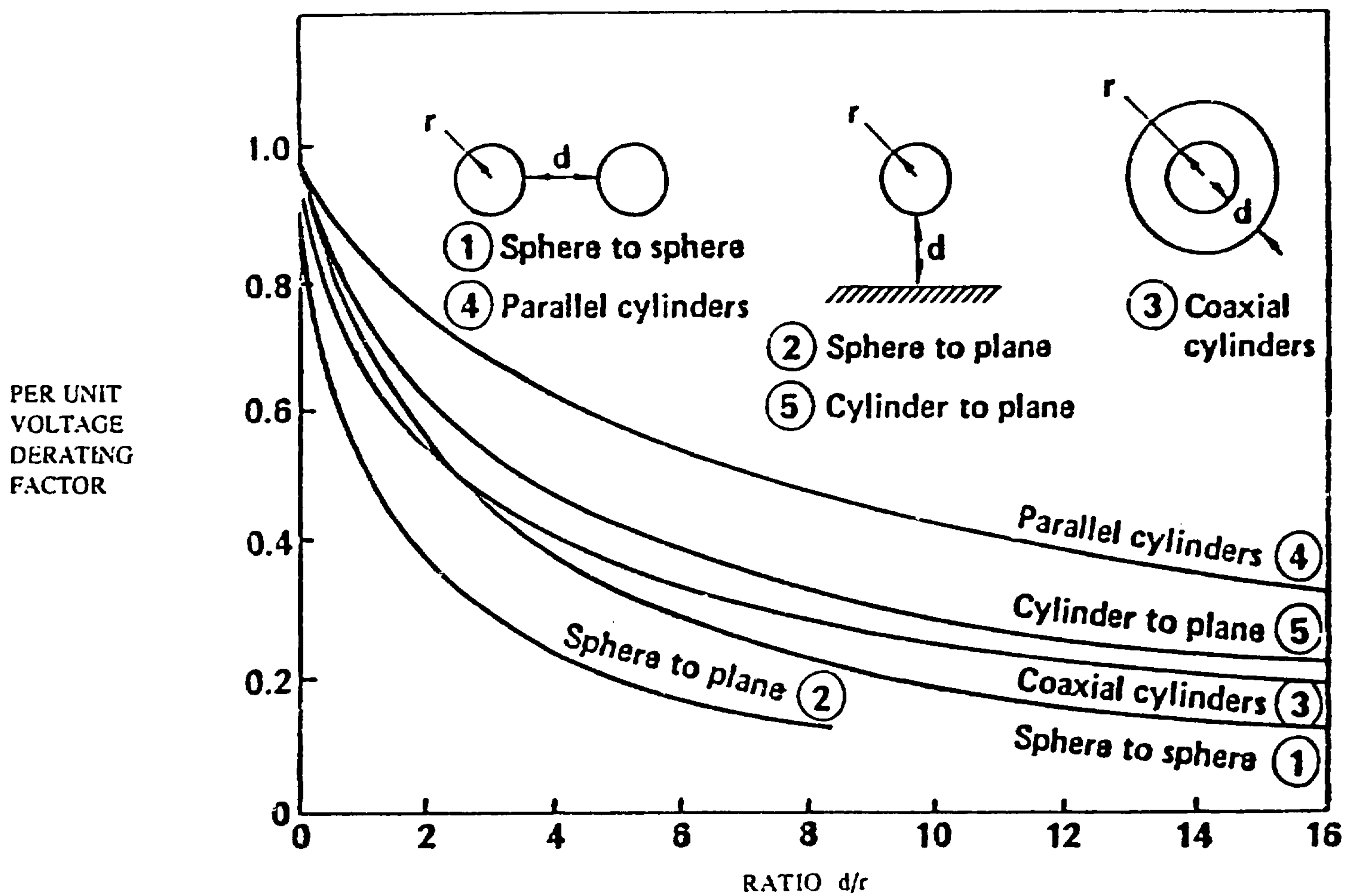


Figure 54. Utilization Factor for Various Electrode Configurations

of the conductor spaced a unit apart in kilovolts per millimeter.

5.1.1 Electric Fields. The space between and surrounding two or more electrodes is pervaded by the electric field. Every point within this space has a definite potential, which is related to its geometric position in the field. The negative gradient of voltage at any point is a vector, which is defined as the electric field-strength E at that point. This gradient can be defined as a force tending to displace a positive charge in the direction of the vector toward the negative electrode. Figure 55 shows a field plot for an energized insulated conductor next to a ground plane. The field lines emanate perpendicularly from the negative electrode and terminate perpendicularly on the positive electrode. Only one field line crosses the gas-solid dielectric interface at right angles: the shortest one. At other points along the interface, the field lines cross at an angle.

A treatise on electric field theory can be found in most texts on electricity and magnetism, or fields and waves. Von Hipple (Reference 4), Greenfield (Reference 5), and Schwaiger and Sorensen (Reference 126) have written texts on dielectrics that explain the basic principles from field theory. Texts describing field plotting and analysis are by Moore (References 127 and 128), Bewley (Reference 129), Smythe (Reference 1), Stratton (Reference 2), and Weber (Reference 3).

5.1.2 Configurations. The best shape and spacing of electrodes in electrical and electronic equipment depends on the physical construction of the equipment, the applied voltage, the type of insulation, the gas pressure, and the operating temperature. For a given electrode spacing and at pressure times spacing values greater than 1500, a spark will jump between small-radius electrodes at lower voltage than between electrodes having large radii (Figure 56). This indicates that, for a given potential difference and spacing, the peak field intensity at the electrodes is smallest when the field is homogeneous (parallel plates) and the field lines are parallel. Most parallel plates must have edges where the field is more intense rather than in the center. By rounding the edges properly, this field can be spread over a

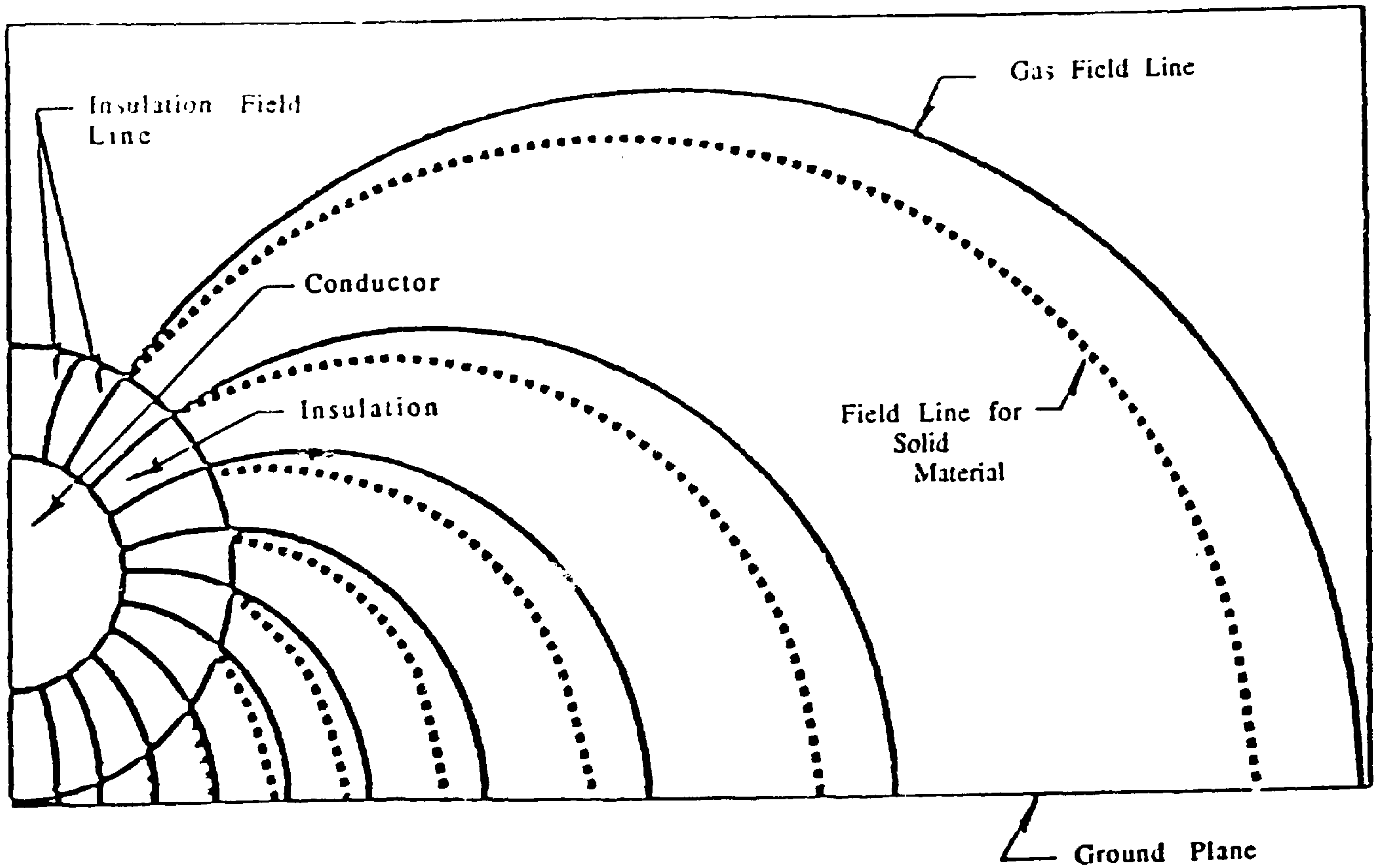


Figure 55. Field Lines Between a High Voltage Conductor and Ground

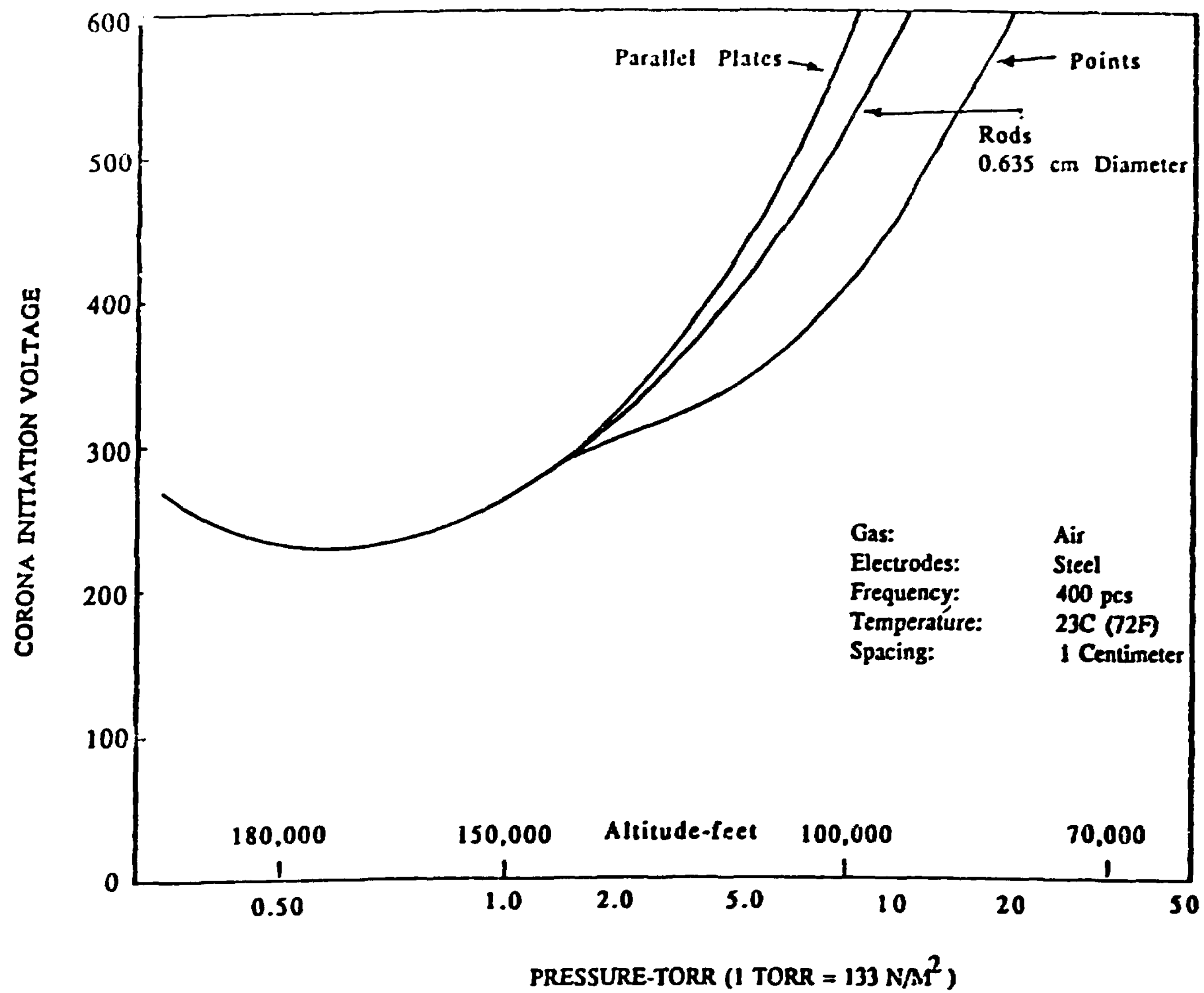


Figure 56. Corona Initiation Voltage Between Points, Rods, and Plates

greater area, reducing the electric field gradient at the electrode (Reference 130).

For electrodes of any given shape, the variation in potential, as a function of the distance from one electrode to the other electrode, can be calculated by solving the differential equations for the electrostatic field. For parallel plates, concentric spheres, and coaxial cylinders, the equations for the field strength (Reference 126) are:

a. Parallel Plates

$$E_x = \frac{\partial \phi}{\partial x} - A = \frac{V}{s} \text{ volts/cm}$$

where:

E_x = voltage gradient at distance x between electrodes in volts per centimeter

ϕ = potential at the electrode in volts

x = distance from the reference electrode in centimeters

A = constant

V = volts

s = spacing between electrodes in centimeters

b. Concentric Spheres

$$E_x = \frac{V}{x^2} \frac{r_1 r_2}{r_2 + r_1}$$

where: $|V_2| > |V_1|$

r_1 = inner sphere (outside) radius in centimeters

r_2 = outer sphere (inside) radius in centimeters

V_1 = reference voltage in volts

V_2 = high voltage applied to opposite electrode in volts

The maximum field gradient E_m is at the surface of the smaller sphere where $X = r_1$ is:

$$E_m = \frac{V}{s}\frac{r_2}{r_1}$$

c. Coaxial Cylinders

$$E_m = \frac{V}{r_1 \ln\left(\frac{r_2}{r_1}\right)}$$

where:

r_1 = inner-conductor outside radius in centimeters

r_2 = outer-conductor inside radius in centimeters

E_m = maximum field gradient at the inner conductor surface in volts per centimeter

Field gradient equations for more complicated electrode configurations are too complex for ordinary design application. Two examples of rigorous solutions for complicated electrodes illustrate the point:

d. Sphere Gap (Reference 126)

The field gradient along the X-axis between two spheres with a charge difference is given below.

$$E_m = \frac{V}{2r}\frac{(1+x)^2}{(1-x)} \sum_{n=0}^{\infty} x^n \left[\frac{1-x^{2n+1}}{(1+x^{2n+1})^2}\right]$$

or:

$$E_m = \frac{V}{2r}\ 1 + \frac{(1+x)^3}{1-x}\left[x\,\frac{1-x^3}{(1+x^3)^2} + x^2\left(\frac{1-x^5}{(1+x^5)^2}\right) + x^3\left(\frac{1+x^7}{(1+x^7)^2}\right) + \cdots\right]$$

where:

r = radius of the sphere in centimeters

x = distance from center of the sphere to the point between the spheres in centimeters.

e. Parallel Cylinders (Ref. 129)

$$E_m = \frac{V}{2r}\left(\frac{1}{\cosh^{-1}\frac{(s/2 - r)}{r}}\right)$$

More difficult field patterns can be rigorously calculated using the techniques of References 1, 2, 3, 126, and 129.

5.1.3 Empirical Field Equations. An empirical field equation or formula is the shortened, simplified form of a rigorous equation. Rigorous equations, manageable with electronic calculators, are still difficult to use in everyday design work; especially if the design has to be assembled piecewise. To derive or compute a rigorous equation is unnecessarily costly and time-consuming, so it is usually more advantageous to use time-proven empirical equations. Furthermore, maximum stress is often the only value needed in a design, and the plotting of the complete field using a rigorous equation is not necessary. Empirical equations for the maximum field stresses at the smaller electrodes for several electrode configurations are given in Table 19 (Reference 131). Electrical stresses calculated with these equations are within 10 percent of values obtained with rigorous equations.

Published empirical equations for sparkover gradients in air and sulfur hexafluoride appear in Tables 4 and 5 (Reference 132). The "typical error" in Table 4 represents the difference between the calculated values and experimental results, except for equations 3.16 and 3.17 in Table 5. Here the values represent differences between the rigorous and empirical equations.

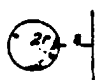
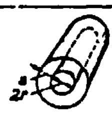
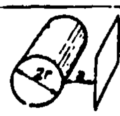
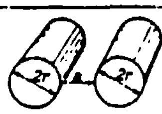
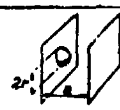
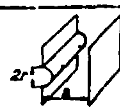
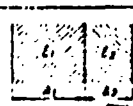
The electrode geometries used in Tables 4 and 5 are shown in Figure 54. Parameters for the equations in Tables 4 and 5 are as follows:

E_s = Sparkover gradient in kilovolts per millimeter

g = Gap length in millimeters

kV = Applied voltage

TABLE 19
MAXIMUM FIELD STRENGTH E WITH A POTENTIAL DIFFERENCE V BETWEEN THE ELECTRODES, FOR VARIOUS ELECTRODE CONFIGURATIONS

Configuration		Formula for E
Two parallel plane plates		$\frac{V}{a}$
Two concentric spheres		$\frac{V}{a} \cdot \frac{r + a}{r}$
Sphere and plane plate		$0.9 \frac{V}{a} \cdot \frac{r + a}{r}$
Two spheres at a distance a from each other.		$0.9 \frac{V}{a} \cdot \frac{r + a/2}{r}$
Two coaxial cylinders		$\frac{V}{2.3 r \lg \frac{r + a}{r}}$
Cylinder parallel to plane plate		$0.9 \frac{V}{2.3 r \lg \frac{r + a}{r}}$
Two parallel cylinders		$0.9 \frac{V/2}{2.3 r \lg \frac{r + a/2}{r}}$
Two perpendicular cylinders		$0.9 \frac{V/2}{2.3 r \lg \frac{r + a/2}{r}}$
Hemisphere on one of two parallel plane plates.		$\frac{3V}{a}$; $(a \gg r)$
Semicylinder on one of two parallel plane plates.		$\frac{2V}{a}$; $(a \gg r)$
Two dielectrics between plane plates (ϵ_1 ϵ_2)		$\frac{V\epsilon_1}{a_1\epsilon_2 + a_2\epsilon_1}$

r_1 = radius of smaller electrode in millimeters

r_2 = radius of second or larger electrode in millimeters

s = spacing, center of r_2 to center of r_1 in millimeters

p = pressure in Pascals

5.1.4 Freehand Field Plotting. For complicated fields, which are very difficult to analyze mathematically, even with a computer, freehand flux plotting by the trial and error method is a recourse. Sufficient accuracy may be obtained for most practical engineering problems by plotting the field with "curvilinear" squares.

5.2 Designs. The principal function of electrical insulation in equipment is to isolate the conductors from each other and their surroundings, restricting current flow to the isolated conductors. This same insulation must support the conductors and parts, and transfer heat away from them. High power, high voltage airborne equipment is densely packaged; therefore, materials with high dielectric strength are required.

5.2.1 Wiring and Connectors. Partial discharges in an electrical circuit, or component, generate noise, which is conducted to connected equipment. Typically, the noise signature is between 20 kHz and 20 MHz. If the partial discharges are extensive, noise can also be induced in low-level neighboring circuits. In high-frequency systems such as radar, the wave shapes of the electrical signals can have partial discharges. These partial discharges produce ozone, optical emission, and acid, which cause deterioration of dielectrics. If corona persists for several hours, the dielectric may start to deteriorate and eventually a breakdown will result.

5.2.1.1. Design Considerations. Voltage, frequency, temperature, ambient gas composition, pressure, radiation, and structural requirements must be known when designing insulation for high voltage equipment. This includes the steady-state operating voltage and also any higher voltage transients, their duration, and their frequency of repetition.

5.2.1.1.1 Gas Pressure. The pressure of gas between spaced electrodes in an electrostatic field is a parameter required to determine the location of the minimum in the Paschen law. This gas pressure between electrodes may differ from the surrounding ambient gas pressure and may vary as a function of time. With higher temperatures and mechanical stress, air trapped in the insulation layers may rupture or force voids in the insulation when the surrounding air pressure is reduced. Figures 57 and 58 show such voids created by gas trapped in layers near the center conductor, and near the outer shield of a coaxial cable.

5.2.1.1.2 Temperature. Each electrical insulation material has maximum temperature limits and temperature-life limits. Therefore, the short-duration temperature and the continuous temperature exposure, both ambient and local, must be known.

5.2.1.1.3 Gases. If the gas between electrodes in the electrostatic field is other than air, Paschen-law curves must be determined for that gas.

5.2.1.1.4 Radiation. Other environmental factors affecting insulation are ultraviolet radiation, nuclear radiation, and exposure to solvents and chemicals. Addition of ultraviolet radiation and chemicals tends to lower insulation breakdown voltage, either instantaneously or as exposure and deterioration progresses.

5.2.1.1.5 Mechanical Requirements. Requirements to be satisfied include shock, abrasion, stability, strength, and flexure from vibration.

5.2.1.1.6 Frequency. Most of the published aerospace partial discharge initiation voltage data are in terms of 60 Hz rather than direct current. A formula for comparing dc data with 60 Hz ac data is $V_{ac} = 0.707\ V_{dc}$. The direct current initiation voltage for point-to-plane electrode configurations is affected by the polarity of the point. The configuration with the point negative breaks down at a lower voltage. The ac initiation voltage always corresponds to the lower value as determined by dc polarity experiments.

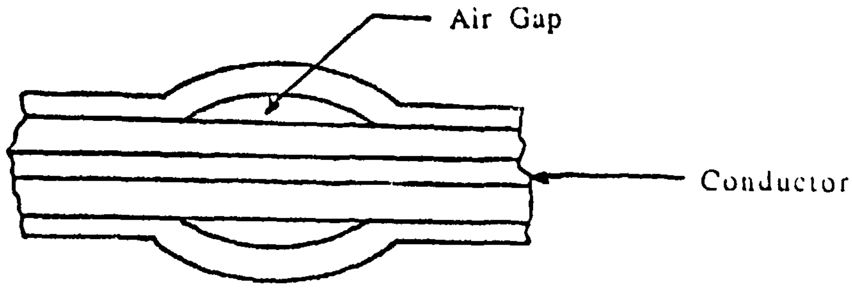


Figure 57. Outer Jacket Rupture

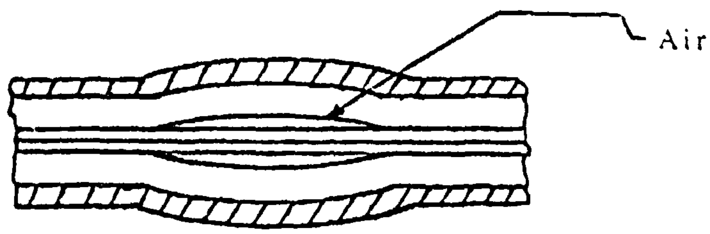


Figure 58. Center Conductor Delamination

At high frequencies, the interference generated by partial discharges is worse than at low frequencies. The rate of deterioration of an insulation by partial discharges is usually proportional to frequency. The dielectric strength of insulators is inversely proportional to frequency. Typical loss of dielectric strength with frequency is shown in Table 20.

5.2.1.2 High Voltage Cable. High voltage wire should be constructed with semiconducting layers of insulation around the stranded center conductor and over the insulation media as shown in Figure 59. In this construction, the air trapped within the stranded center conductor is not electrically stressed and need not be eliminated. The insulation can be made advantageously of several layers, with the dielectric constant (ε) of each layer being successively higher toward the center. The voltage gradient can then be maintained nearly constant from the inner conducting layer to the outer conducting layer, rather than being much higher near the inner conducting layer (Figure 60). An example follows:

In a coaxial configuration having three layers of insulation (Figure 59), the voltage stress is not constant across any layer of insulation. In the inner insulation, $\varepsilon_1\rho_1$, the stress (E_1) adjacent to the conductor is in volts per unit of distance

$$E_1 = \frac{V_1}{r_1 \ln\left(\frac{r_2}{r_1}\right)}$$

The symbols are defined in Figure 59. The stress within the outer surface of the inner insulation is

$$E_1 = \frac{V_1}{r_2 \ln\left(\frac{r_2}{r_1}\right)}$$

At the same time, the stress in the $\varepsilon_2\rho_2$ insulation just outside of the interface from insulation $\varepsilon_1\rho_1$ is

TABLE 20a

POLYETHYLENE-DIELECTRIC STRENGTH, V/MIL, FOR 30-MIL SHEETS AS A FUNCTION OF TEMPERATURE AND FREQUENCY

	FREQUENCY						
Temp., °C	60 Hz	1 kHz	38 kHz	180 kHz	2 MHz	18 MHz	100 MHz
-55	1,660	1,270	750	700	410	190	160
25	1,300	970	500	460	340	180	130
50	1,140	910	590	580	280	150	150
80	980	970	440	430	220	150	150

TABLE 20b

TEFLON-DIELECTRIC STRENGTH, V/MIL, FOR 30-MIL SHEETS AS A FUNCTION OF TEMPERATURE AND FREQUENCY

	FREQUENCY						
Temp., °C	60 Hz	1 kHz	38 kHz	180 kHz	2 MHz	18 MHz	100 MHz
-55	1,080	940	660	600	400	240	160
25	850	810	540	500	380	210	140
50	800	770	530	500	360	210	140
85	780	670	530	480	360	220	140
125	870	630	560	520	350	220	140

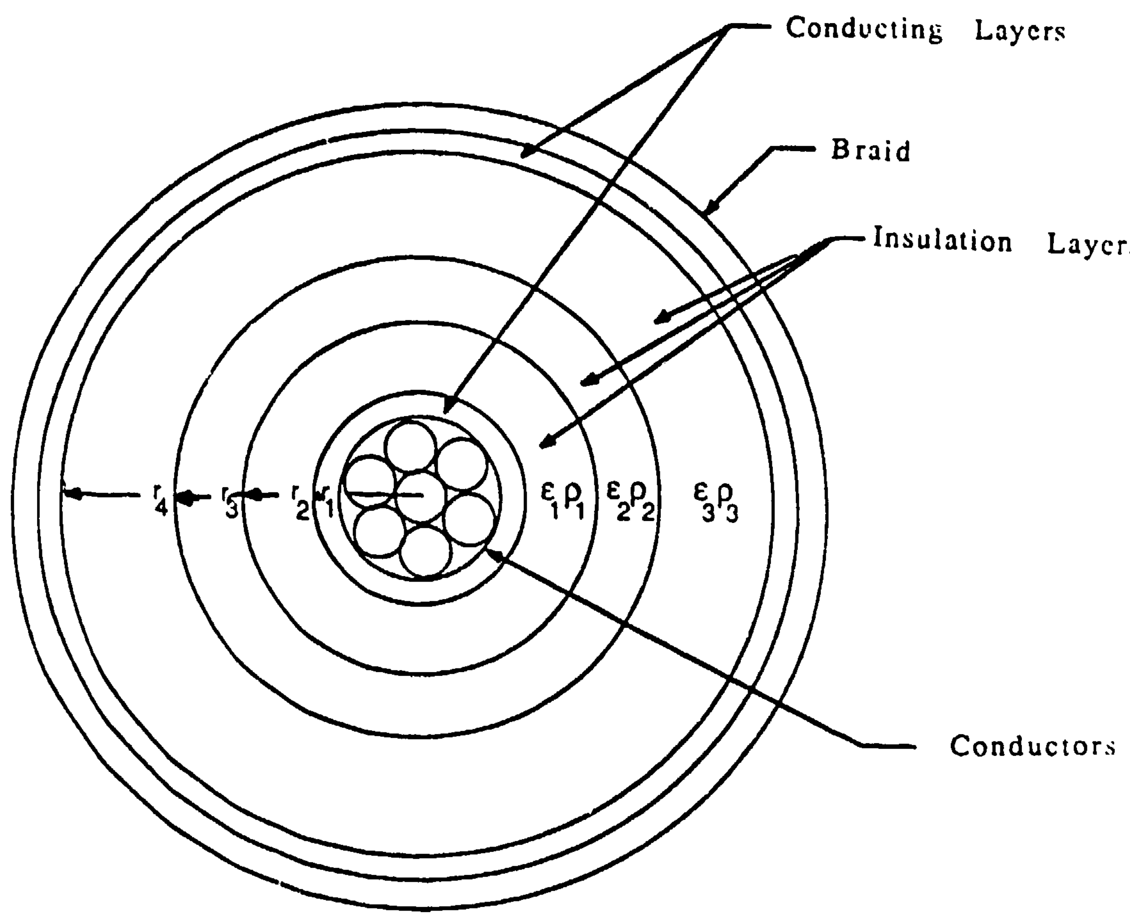


Figure 59. High Voltage Wire

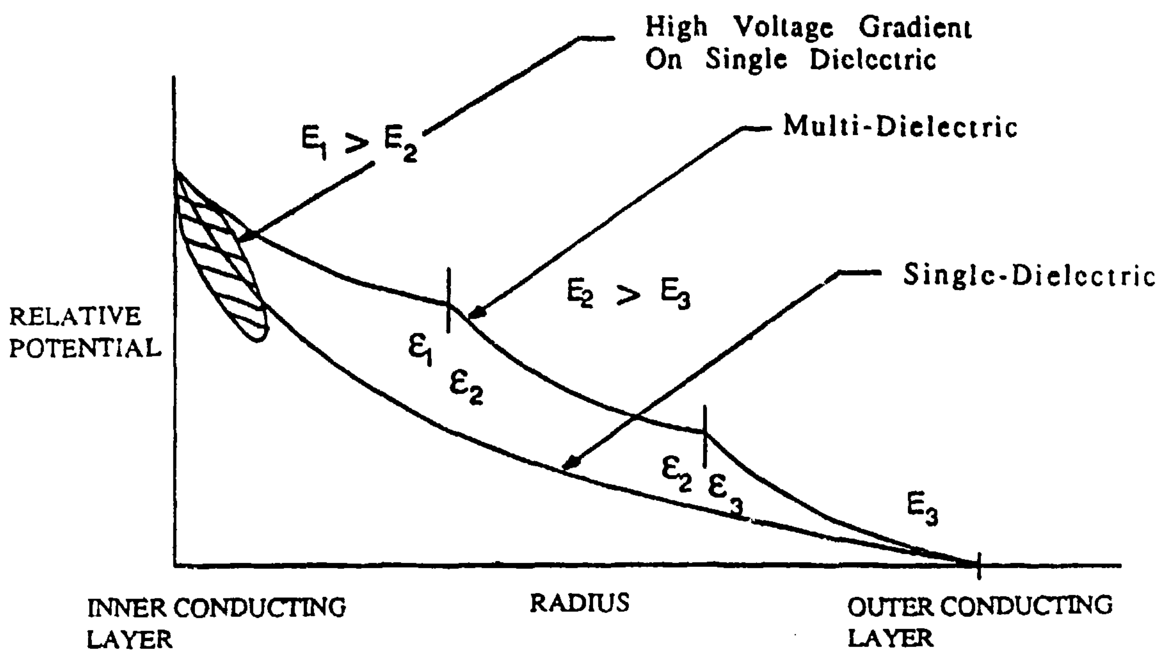


Figure 60. Field Gradient for Single and Multiple Layer Dielectric

$$E_1 = \frac{\varepsilon_1}{\varepsilon_2}\left(\frac{V_1}{r_2 \ln\left(\frac{r_2}{r_1}\right)}\right)$$

Continuing in this manner through insulation layer $\varepsilon_3\rho_3$, we can derive an expression for the voltage at the outer surface of the inner layer of insulation.

$$V_0 = \frac{V_1 \varepsilon_1}{\ln\left(\frac{r_2}{r_1}\right)}\left[\frac{\ln\left(\frac{r_2}{r_1}\right) + \ln\left(\frac{r_3}{r_2}\right) + \ln\left(\frac{r_4}{r_3}\right)}{\varepsilon_1 + \quad \varepsilon_2 + \quad \varepsilon_3}\right]$$

The other interface voltages can be similarly calculated.

The voltage stress and total allowable voltage when dc is applied to the coaxial configuration in Figure 59 can be calculated similarly. The stress at the conductor is given by

$$E_1 = \left[\frac{V_1}{\ln\left(\frac{r_2}{r_1}\right)}\right]\frac{1}{r_1}$$

The stress at the interface between insulation $\varepsilon_1\rho_1$ and $\varepsilon_2\rho_2$ changes as one crosses the interface. In insulation $\varepsilon_1\rho_1$, the stress is

$$E_1' = \left[\frac{V_1}{\ln\left(\frac{r_2}{r_1}\right)}\right]\frac{1}{r_2}$$

while in insulation $\varepsilon_2\rho_2$, the stress is

$$E_2' = \left[\frac{V_2}{\ln\left(\frac{r_3}{r_2}\right)}\right]\frac{1}{r_2} = \left[\frac{V_1}{\ln\left(\frac{r_2}{r_1}\right)}\right]\frac{1}{r_2}\left[\frac{\ln\left(\frac{r_3}{r_2}\right)}{\ln\left(\frac{r_2}{r_1}\right)}\right]\frac{\rho_2}{\rho_1}$$

and finally

$$V_0 = V_1 \left[\frac{\rho_1 \ln\left(\frac{r_2}{r_1}\right) + \rho_2 \ln\left(\frac{r_3}{r_2}\right) + \rho_3 \ln\left(\frac{r_4}{r_3}\right)}{\rho_1 \ln\left(\frac{r_2}{r_1}\right)} \right]$$

5.2.1.3 <u>High Voltage Connectors</u>. Connectors must also be designed to eliminate air voids between conducting surfaces. One successful method is to make one side of the mating-interface from soft, pliable insulation (Figure 61). When mated, the pliable insulation conforms closely to the opposite dielectric. The pliable insulation should first contact the molded insulation near the center conductor, then the contact should progress out to the shell without trapping air between the two contact surfaces.

A thin layer of silicone grease may be applied to the insulation surfaces of some connectors to fill micropores in the insulation. Too much grease (more than 5 mils) tends to (1) prevent complete closure of the connector, (2) introduce air cavities, or (3) deform the pliable insulation. Therefore, silicone or other additives are not recommended for properly constructed high voltage connectors.

5.2.1.4 <u>Connector Test Data</u>. There are two basic types of high voltage connector designs: multi-pin connectors for power and electronic equipment, and single-pin connectors between electronic packages and high voltage power supplies.

Closely spaced, small pin, multi-pin connectors are not recommended for high-voltage unpressurized equipment, especially if there is a probability that the voltage between pins will exceed 450 volts peak in the pressure region between 50 and 0.1 Pa. This problem was demonstrated by a three-part evaluation test of a 55-pin connector. Figure 62 illustrates the pin construction and indicates the air gaps of the test article. The corona onset voltage was measured between pins of a mated 55-pin connector in a simulated high-altitude chamber. The tests were performed with the connector shell

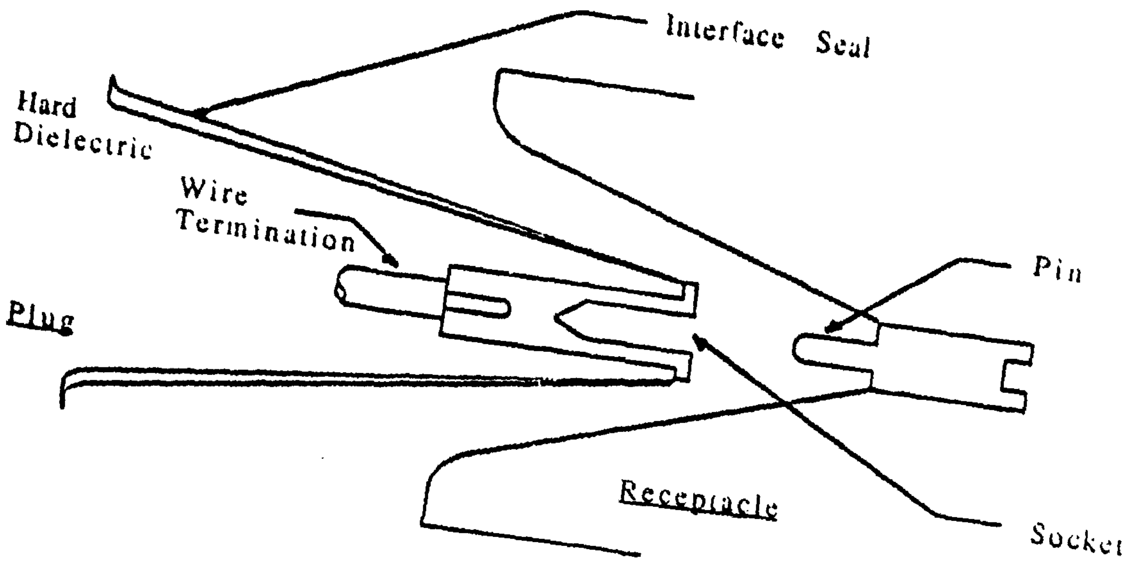


Figure 61. High Voltage Connector

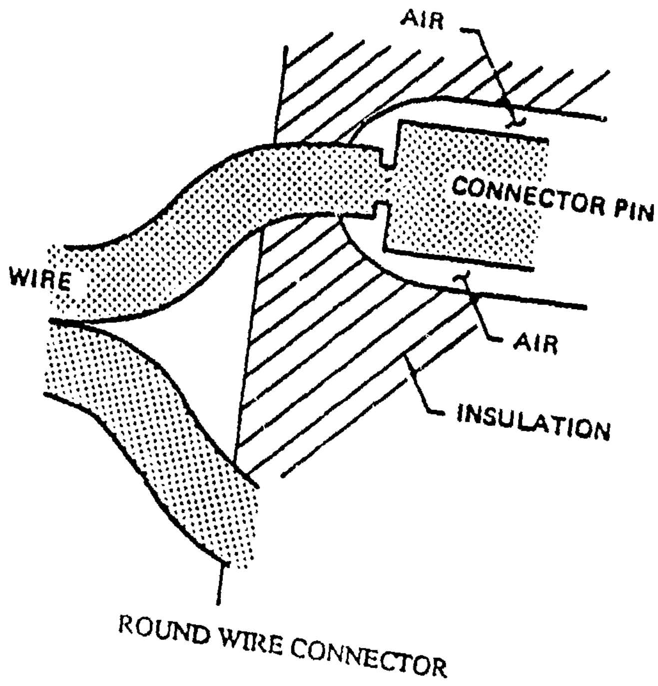


Figure 62. Round Wire Connector

electrically grounded and the connecting wires and unwired pins encapsulated with 1.25-mm silicone rubber on each end of the connector. In the first test, a pair of 22-gauge, twisted, Teflon-insulated wires (0.025 mm thick) were connected to adjacent connector pins and then fed through the vacuum chamber wall to the corona test facility. The second test was like the first except that the wires were connected to nonadjacent pins. In the third test, one lead was disconnected from the assigned pin and then reconnected to an adjacent pin on the other mating half of the connector to eliminate the possibility of partial discharges between the parallel conductors.

The contacts within a connector must float to allow for manufacturing tolerances and pin insertion and extraction. To do this, small spaces surround each contact. Furthermore, small air gaps will form about the wire insulation unless the insulation is pressed firmly against the contact. Many connectors are made with spring-loaded or crimp contacts, which leave an air gap above each contact (Figure 62). These air gaps are ideal for partial discharges; that is, the air gaps are located in the highest field stress volumes.

The curves drawn from the test data are shown in Figure 63. The data show that the highest corona onset voltage was derived from the test in which the pins were energized from opposite connector halves. In this test, the onset voltage for the connector was less than that of wires spaced 5 cm apart (the length of the connector) and greater than that of twisted, closely spaced conductors. This low-corona onset voltage exhibited by the connector is due to air passages within the connector construction, as shown in Figure 62. This connector configuration has been designed for too low a voltage between pins to provide adequate high voltage design practice. Curves for the other two tests have corona onset voltages equal to those of twisted insulated conductors (Reference 133).

5.2.1.5 Feedthroughs. Some feedthroughs are designed with a shallow well around each termination or pin (Figure 64). These wells must be completely filled with an encapsulant or provided with a generous opening for outgassing to space. The well, if left open or partially filled with encapsulant, will be subject to partial discharges, even at low voltages. The voltage across a bubble

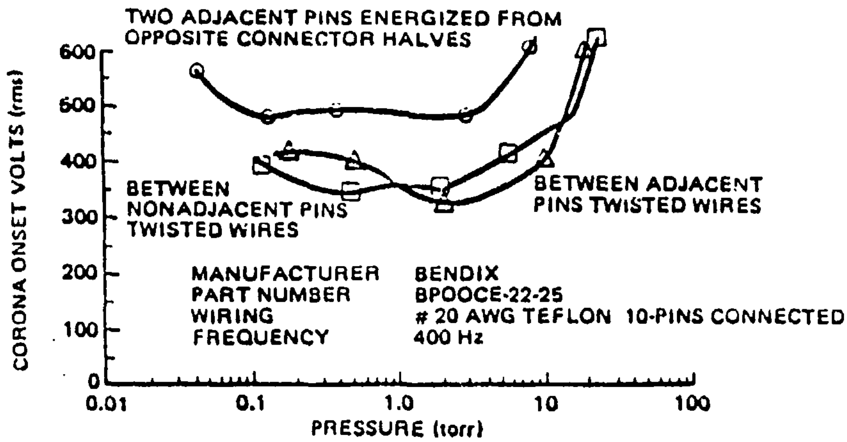


Figure 63. Connector - 55 Pins in Air at 24^0 C. Terminals Not Potted

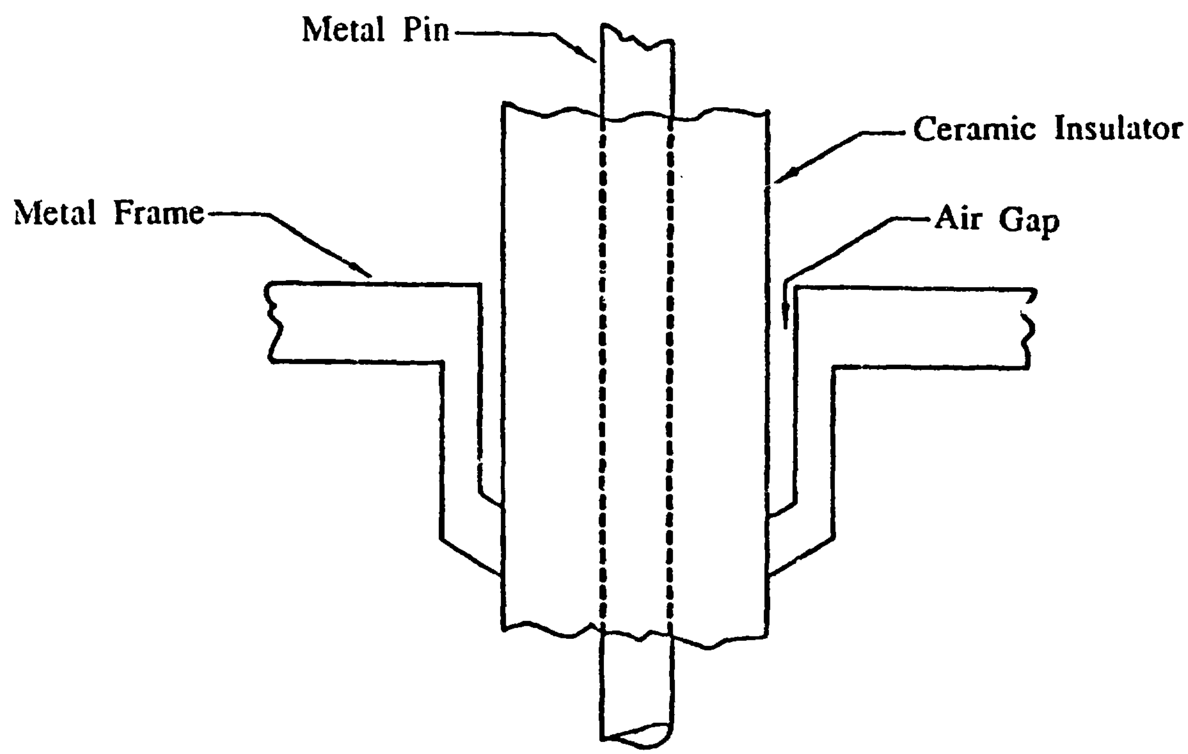


Figure 64. Connector Pin with Air Gap

at the bottom of the well can be found by corona testing the encapsulated article between each pin and the metal frame. The feedthrough shown in Figure 65 is an excellent design. It is designed with corona shields on each end and has no air gaps between the conductor and metal base plate.

Occasionally it is necessary to pass several conductors through a wall evacuated on one side and pressured on the other side. It must be remembered that the small spaces between the conductor strands are like small air pipes. To be successful, it is required that the wire strands in that section be completely filled with a potting compound or solder to work. It is best to use solder with a solder ball or corona shield surface as shown in Figure 66. The "solder balls" should be in the center of the feedthrough. The potting material should be allowed to penetrate the conductor ends to seal the insulation.

Vented connectors will not perform properly if used in an airplane or aerospace plane. It takes too long for the connectors to vent; thus, a high probability of partial discharges results.

5.2.1.6 Wire Terminations. High voltage interconnections between power supplies and electronic circuits are difficult to design, assemble, and assess, especially if the interconnecting shielded wire is flexed or strained after it is attached to one or both terminals. Linear stressing can break one or all of the bonded joints between the shield, conductor, or wire insulation and the terminal and encapsulating material. Any delamination at the insulation bond will form a void (air gap) and result in corona and eventual voltage breakdown. When the wire is bent at the terminal (Figure 65), and the high voltage conductor is flexed or stressed, there is a probability of delamination at the wire-encapsulant surface.

The wire shield and insulation preparation are as important as the connection. One method of preparing the wire termination is to cut the wire and shield to length, and then place three or more turns of a small conductor or formed metal ring over the end of the wire shield and insulator as shown in Figure 67. This method holds the shield end strands in place and forms a round conformal metal surface at the end of the shield. When three or more turns of

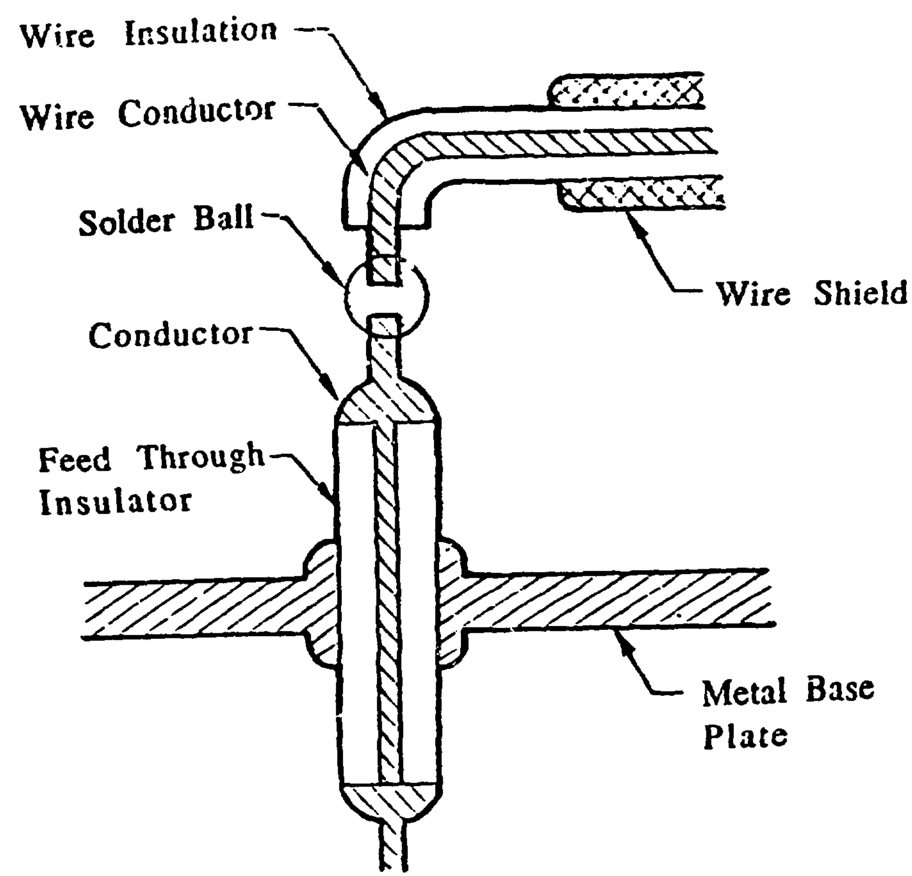


Figure 65. Acceptable Standoff Connection

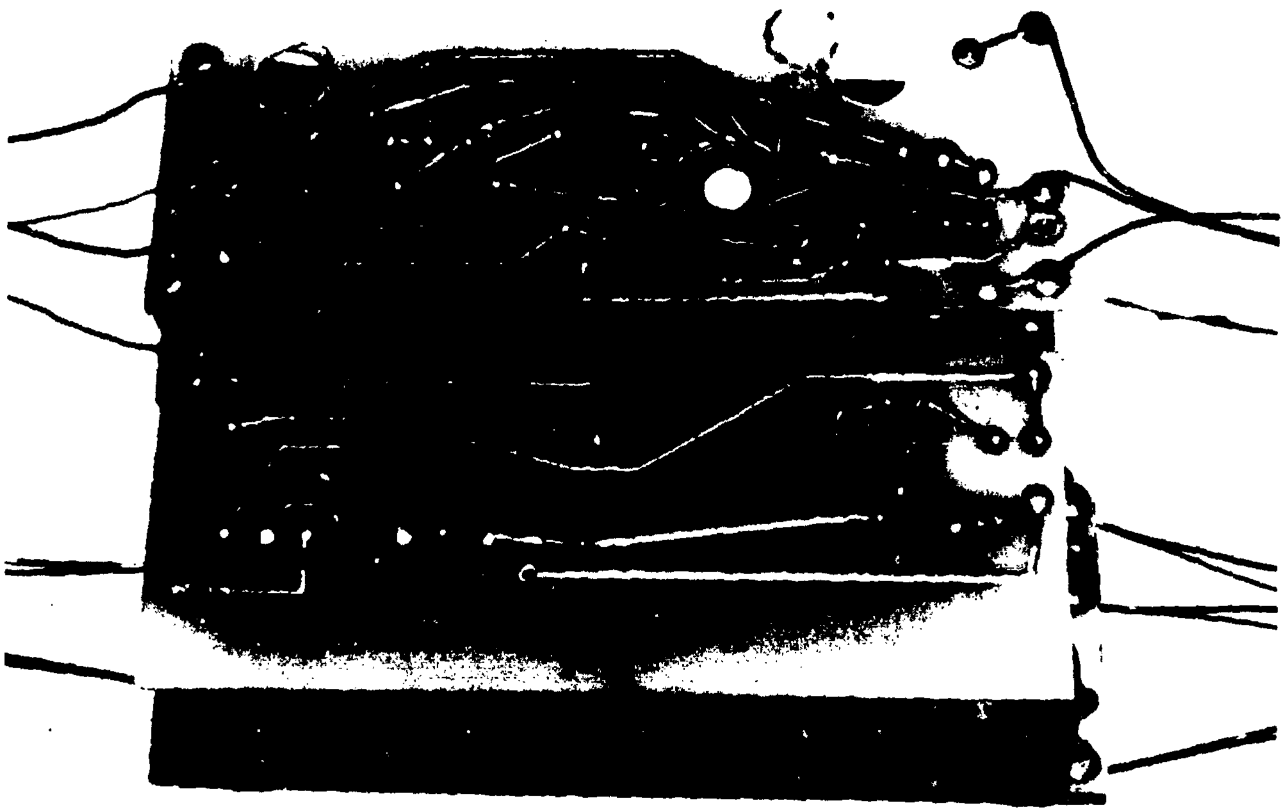


Figure 66. Solder Ball Connections

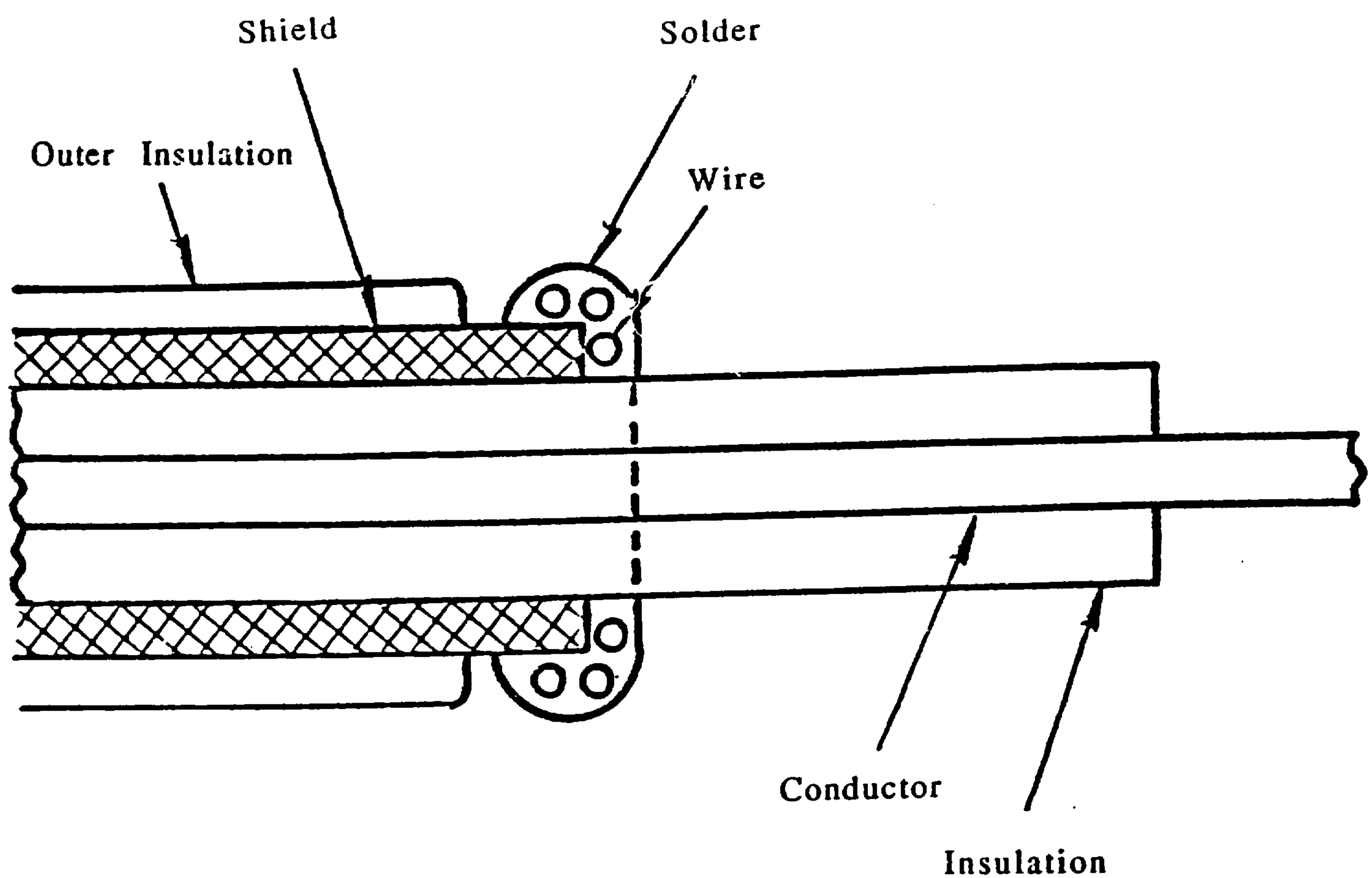


Figure 67. Wire Termination

wire are used, as for breadboard demonstration, the wire should be soldered in place with a low-heat iron so that its insulation will not be melted or deformed.

If Teflon insulation is used, it is necessary to etch the Teflon. This etching should be done within a few hours before encapsulation. If the etching material is placed on the Teflon for more than 24 hours at room ambient temperature before encapsulation, or if the Teflon is heated because of soldering, the Teflon will cold-flow and ruin the usefulness of the etching. If the etching must be applied more than 24 hours before encapsulation, it is recommended that the etched surfaces be kept cold to prevent cold-flow.

Solder joints on circuit boards, especially printed circuit boards, are designed to have minimum solder. This leaves the electrical post termination protruding through the solder on the circuit interconnection. Often the post terminal is clipped after soldering, leaving sharp edges protruding above the circuit metal surface. This is unacceptable for circuits with voltage exceeding 250 volts peak. Sketches of acceptable and unacceptable solder joints for high voltage circuits are shown in Figures 68 and 69. Whenever there is a solder-draw or sharp edge protrudes from a circuit, the probability of corona and voltage breakdown is enhanced. First, the conformal coating applied to the circuit board and circuits may not cover the sharp point or edges. Second, solder has more free electrons than a conformal coating. It can be assumed that a solder electrode has corona onset and breakdown of 85 percent of that of steel (these data are taken from test). Third, any ionization from a solder joint will result in surface heating of the solder, and the solder will tend to evaporate a thin layer across the insulation surface between conductors, resulting in tracking and arc over. This phenomenon will take only a few minutes between high voltage conductors.

5.2.2 Resistors. Solid-core resistors should be used throughout the high voltage module. Hollow-core resistors, if sealed on the ends, will slowly depressurize at high altitude and arc from end to end along the hollow-core surface.

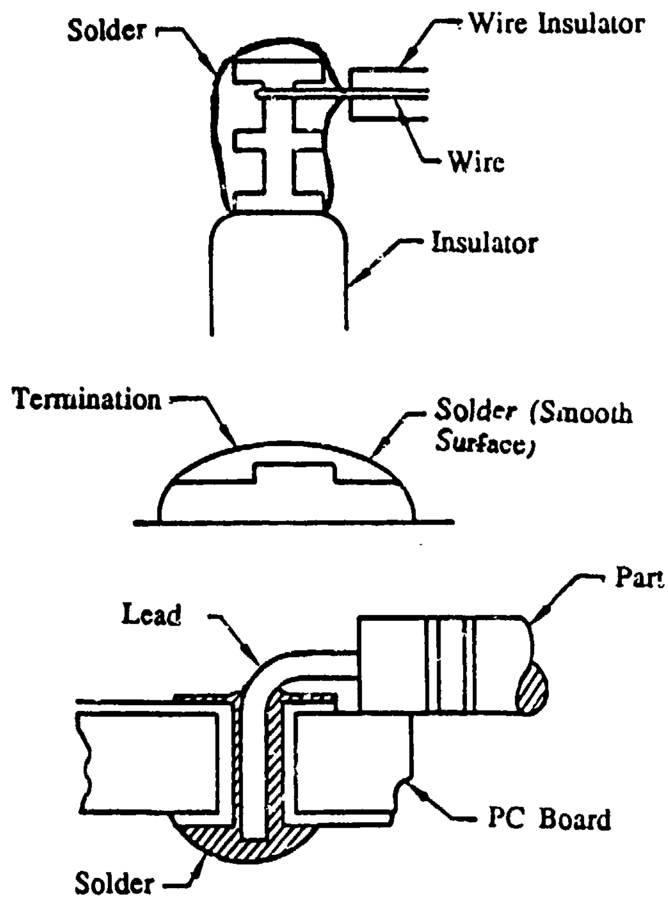


Figure 68. Acceptable Termination

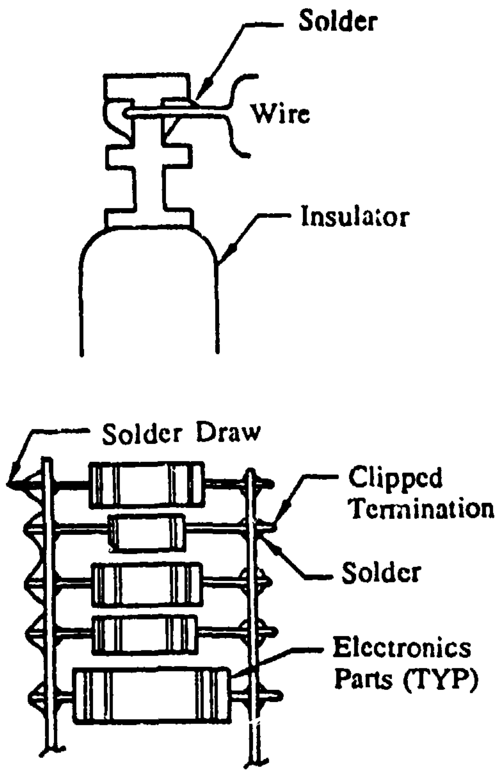


Figure 69. Unacceptable Soldered Terminations

Resistor coatings can be a problem. One supplier made resistors with light or dark blue coatings. The light blue coatings were well bonded to the elements. The dark blue coatings tended to debond. The resulting air gaps then depressurized and the resistors failed.

5.2.3 Capacitors. Dielectrics used for high voltage capacitors, include liquids, liquid-impregnated paper or film, electrolytics, plastic film, paper-plastic combinations, mica, ceramics, glass, compressed gas, and vacuum. Unless special requirements, with respect to temperature, stability, radiation resistance, or packaging are involved, liquid-impregnated paper or plastic film offer the best energy-space-cost combination and, consequently, are more widely available for high voltage capacitors.

This section deals only with high voltage capacitors. Many dielectric configurations that are quite appropriate for low voltage, high performance capacitors used in solid-state communication equipment are not applicable to high voltage work, and are not covered here. This excluded category includes electrolytic and ceramic-insulator capacitor types.

5.2.3.1 Design Features. The most important design features of capacitors are low dissipation factor, high dielectric stress, and yields at acceptable failure rate. Dc capacitors for continuous duty also require a low dissipation factor because some ac ripple is usually present. High insulation resistance is usually required for applications. Dc energy storage capacitors require design features that permit extremely high currents as well as very fast charge and discharge rates.

5.2.3.1.1 Construction and Processing. Series connection of sections necessitates careful attention to conductor insulation, clearances, geometry, and workmanship, while the necessity for liquid impregnation requires meticulous control of initial material purity, as well as preventing contamination during processing.

5.2.3.1.2 Dielectrics. Liquid impregnation is the most effective means of ensuring corona-free performance at rated voltage. All papers and films have

surface irregularities that trap air when stacked between metal electrodes. Unless the air is replaced by a liquid with dielectric constant reasonably close to that of the paper or film, the stress distribution under an applied potential will be such that the highest stress will appear across the air pockets. Because the air has a dielectric strength far lower than the paper, film, or liquid, it will ionize and initiate partial discharges at a potential much lower than that required if no air were present. Under dc-voltage stress, the mechanism is similar, except that the stress distribution is controlled by the resistivity of the dielectric materials rather than by their dielectric constants. Another advantage of liquid impregnation is replacing air with higher dielectric strength liquids that results in a more compact capacitor.

Impregnation with solids such as waxes or resins is feasible for some applications, but has not been found to be reliable for operation at voltages above 225 volts rms because of susceptibility to partial discharge damage. Unimpregnated plastic film capacitors are also suitable for applications, but are subject to partial discharge damage at ac voltage above 225 volts rms unless special design features are provided.

5.2.3.1.3 Essential Design Features. In addition to the requirements listed in Table 21, all types of high voltage capacitors must be made from dielectric materials having the highest available dielectric strength and having the longest demonstrated life at rated stress.

Dielectrics successfully used in high voltage capacitors include, but are not limited to the materials shown in Table 22 and the following materials:

a. Polystyrene dielectric capacitors. Capacitors of polystyrene dielectric, because of their low dielectric absorption and radio frequency losses, are intended primarily for use in calculators, computers, integrators, time-base oscillators, laboratory standards, and other pulse applications. The outstanding characteristics of these capacitors are low-temperature performance characteristics and stability.

TABLE 21

CAPACITOR REQUIREMENTS

AC Capacitors	DC Capacitors	Energy Storage Capacitors
Low dissipation factor	Low dissipation factor	Low equivalent series resistance (ESR)
High partial discharge threshold	Low insulation resistance	Low insulation resistance
		High current capacity
		Low inductance

TABLE 22

ACCEPTABLE IMPREGNATES

Impregnates	Dielectric Constant
Tricresyl Phosphate (TCP)	6.9
Monoisoprophyl Biphenyl (MIPB)	2.5
Silicone Oil (DC-200)	3.6
Diallyl phthalate Monomer (DAP)	10.0

b. Polyethylene terephthalate dielectric capacitors. Capacitors of polyethylene terephthalate dielectric are intended for use in high-temperature applications similar to those served by hermetically sealed paper capacitors, but where higher insulation resistance at the upper temperature limits is required.

c. Paper and polyethylene terephthalate dielectric capacitors. Capacitors of paper and polyethylene terephthalate dielectric are intended for applications where small case sizes and high-temperature operation are required.

d. Polytetrafluoroethylene dielectric capacitors. Capacitors of polytetrafluoroethylene dielectric are intended for high-temperature applications that require high insulation resistance, small capacitance change, and low dielectric absorption. These capacitors exhibit excellent insulation resistance values at high temperatures.

e. Castor oil and cyanoethyl sucrose. These impregnating liquids tend to freeze at -20°C and are unacceptable for airborne equipment.

f. Acceptable impregnates. Acceptable impregnates for high voltage capacitors include, but are not limited to, the materials, listed in Table 22.

g. K-F polymer/silicone oil. Polyvinylidene fluoride film (K-F polymer) impregnated with silicone oil performs well in pulse capacitors.

h. K-F polymer/DAP. K-F polymer impregnated with diallylphthalate has excellent radiation resistance, but some interaction was observed between the DAP and K-F polymer (Reference 134).

i. Polysulfone film. Polysulfone film is an acceptable film for high voltage capacitors (Reference 135).

5.2.3.2 Failure Modes and Mechanisms. Failure modes in capacitors include short circuits, open circuits, and parameter drift. Failure by short circuiting

is by far the most frequent failure mode. Shorts may result from one of many mechanisms. The most common is electrical breakdown caused by conducting sites or electrically weak areas in the dielectric. Conducting sites may be particles embedded in the paper, airborne particles picked up during assembly, foil slivers, or products generated by partial discharge. Weak areas may result from torn paper, thin spots, or dielectric layers missed during assembly.

Even a moderate-sized capacitor has many square centimeters of dielectric, which must be ultra thin to achieve reasonably small volume. Consequently, stresses in capacitor dielectrics are usually far higher than in dielectrics used in other insulation applications. Measures to ensure the highest possible electrical strength and longest life of capacitor dielectrics include multilayer pads, liquid impregnation, use of series connections for voltage ratings above 2500 volts, assembly in a controlled environment, high potential testing, and, in some cases, burn-in at elevated voltage and elevated temperature.

Even the best dielectric papers contain a finite number of conducting particles of randomly distributed sizes. These particulate defects are also distributed randomly across the area of the papers. Multilayer construction has the least chance of having a conducting particle completely bridge the foil electrodes. Because the thinnest paper contains the most conducting particles (full thickness of paper) per square foot, it is desirable to use the thickest paper possible to keep the number of particles low. However, the thinnest possible paper gives the highest capacity per unit volume. A compromise is, therefore, necessary.

The dielectric strength of a paper pad increases with the number of layers up to four or five layers. Above this number the increase in strength is no longer proportional to the increase in number of layers. There is also an apparent decrease in electrical strength per unit thickness with individual paper thicknesses greater than 0.75 mils. This phenomenon appears to be an effect of the voltage gradient across the dielectric. It becomes advisable to

assemble the capacitor by connecting sections in series rather than using thicker pr .

Plastic films such as polyethylene terephthalate (Mylar) are able to withstand stresses as high as impregnated paper can, but the resulting capacitors are generally larger and more expensive for the same performance. Liquid-impregnated paper-polypropylene sandwich dielectrics are competitive with liquid-impregnated paper but not as widely used because there are fewer reliable sources of supply.

Parameter drift and open circuits are failure modes not commonly encountered in high voltage capacitors; however, there have been instances when inexperienced manufacturers have tried to make connections to the aluminum foil electrodes by pressure contact rather than by soldering or welding. This is always disastrous because aluminum oxides form, which generate open circuits under low voltage stress and destructive arcing under ac conditions.

With liquid-impregnated capacitors, the container terminations and seals are important. All free space must be filled with liquid to exclude gas that can readily ionize. Rectangular or oval cases are designed with enough flexibility to permit the liquid to expand and contract as temperature and pressure change. Cylindrical or rigid-walled cases must be designed with enough flexibility to permit the liquid to expand and contract as temperature and pressure change. Cylindrical or rigid-walled cases must be designed with provisions that prevent low-pressure gas accumulation between plates.

5.2.3.3 Effects of Partial Discharges. The life of an insulating material depends on the type, the operating temperature, voltage stress, applied voltage, physical dimensions, material control during manufacture, and cleanliness. Of equal importance are small defects in the layers of conducting foil and insulation, which may become gas-filled voids Partial discharges can be generated when the gas is overstressed. These discharges are accompanied by electron bombardment, which generates hot spots and interacts with the gas to produce ozone and nitrous oxides that decompose surrounding materials.

Damage to the electrical insulation by electron bombardment and chemical deterioration can be identified by a decrease in insulation resistance and an increase in the dissipation factor. Dielectric materials are often evaluated with breakdown tests, and superior materials are expected to exhibit higher breakdown voltages. A breakdown test is useful in finding flaws in the insulation; however, when a solid dielectric is to be impregnated with a liquid or when air voids may be present, the value of a breakdown test may be limited because breakdown values are usually considerably higher than the voltage at which the insulation is used. This point is illustrated in Figure 70, which shows the relative breakdown values, indicative of partial discharges and the range of the useful electrical stresses for design purposes.

The partial discharge inception voltage is very important because a capacitor, if permitted to operate with internal partial discharges, will soon fail. Figure 70 illustrates data taken for polyethylene insulation. Other insulation materials will degrade similarly.

5.2.3.4 Impregnated Paper. As impregnating dielectric liquids are overstressed and aged, their molecules polymerize. High temperature and electrical stress accelerate the polymerization process. In time, continued electron bombardment will carbonize the polymerized molecules, causing voltage breakdown or puncturing through the insulation.

5.2.3.5 Gas Voids. The partial discharge initiation voltage for gas-filled voids is much lower for solid and impregnated paper dielectrics. Gas-filled voids result from incomplete impregnation during manufacture and must be detected and eliminated. Dry unimpregnated areas in the insulating paper contain minute voids. Gas-filled voids may also exist at the ends of the individual layers of insulating paper. Further, small wrinkles may be formed in the capacitor foil during manufacture. If these small wrinkles are not completely impregnated or filled with solid or liquid insulation, they may become sites for gas bubble accumulation.

The temperature of the partial discharge across the center of a gas-filled void could be as high as 4,000°K. (Reference 6) The gas itself will be

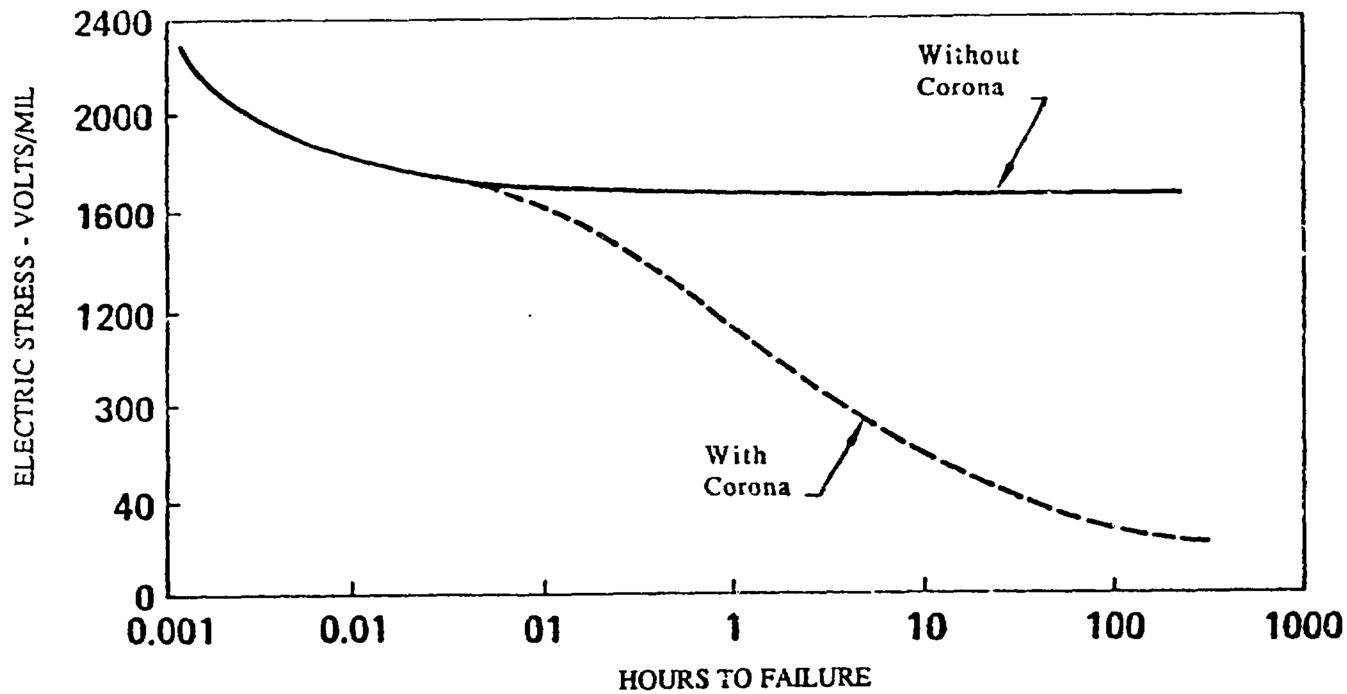


Figure 70. Dielectric Life of Polyethylene With & Without Corona

much cooler than the discharge channel (around 550°C.). The partial discharge inception voltage (PDIV) across a gas-filled void can be as low as 230 volts rms at the Paschen-law minimum. After gases such as hydrogen or a hydrocarbon gas evolves, the PDIV can decrease 185 to 200 volts, depending on the breakdown characteristics of the gas or gases and thickness of the series dielectric.

5.2.3.6 Failure Rate Prediction. Capacitor life, as expected, depends on voltage stress and temperature. The relationship can best be described by a failure rate expressed as the percentage of failures (per 1000 unit-hours) based on a specific confidence level. In continuous operation at rated voltage capacitors exhibit a relatively high initial failure rate which lasts a few hour-decades. This initial failure regime is followed by years of essentially constant or slightly decreasing failure rate, which finally leads to a rapidly increasing failure rate as "wearout" become predominant. This is illustrated by the classical "bathtub" shaped curve (Figure 71).

It is feasible to relate life or long-term breakdown to commonly used values of dielectric strength. Dielectric strength is measured in the laboratory on small specimens for a "life" on the order of 60 second End-of-life breakdown levels of a large specimen, such as a capacitor, are subject to long-term stressing, to an area effect, and to long term chemical and physical changes.

A review of those data shows a trend for partial discharges to vary over the life of a dielectric. The measured partial discharges for a new capacitor will have a multitude of low-energy partial discharges with a few high-energy partial discharges as shown in curve a, Figure 72. As the dielectric ages, the number of high-energy partial discharges increases indicating there is an increase in dielectric heating and failure is imminent, as shown in curve b, Figure 72.

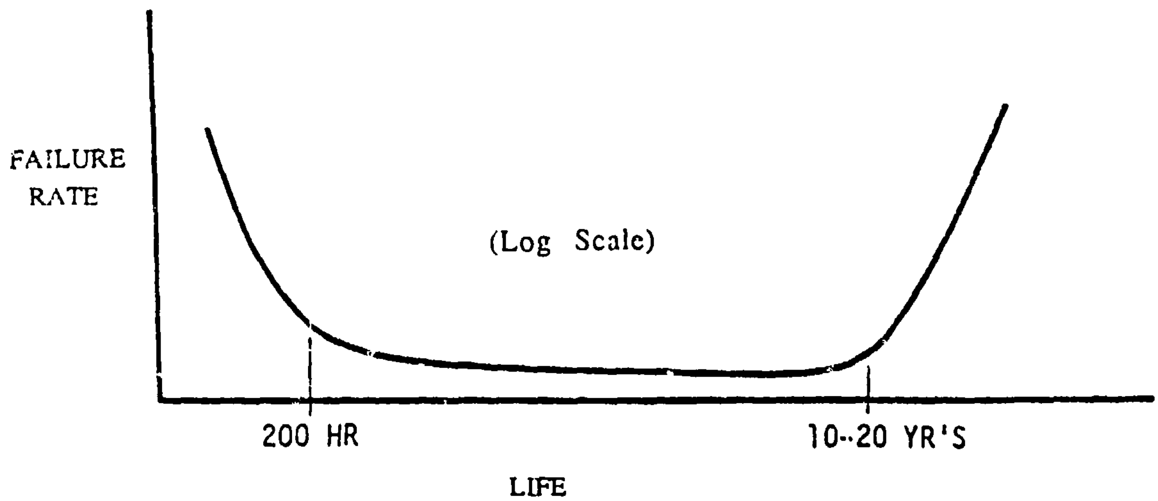


Figure 71. Failure Rate of Coils

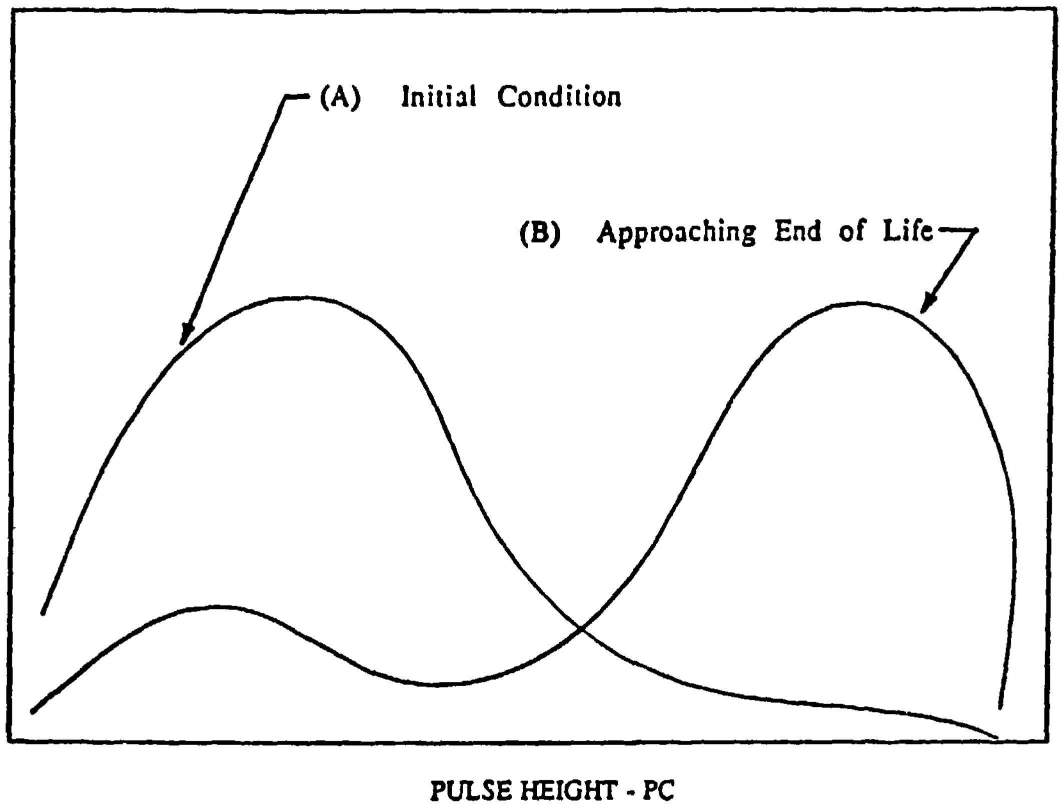


Figure 72. Change in Partial Discharge Signature with Time of Operation

Voltage ratings of capacitors are based on life tests performed on many samples at numerous voltages and temperatures. Short-time overvoltage tests during specific manufacturing stages screen out grossly defective parts, but cannot be depended on to reject marginal parts. A burn-in at elevated voltage and temperature is effective in reducing early failure of capacitors when reliability is more important than cost. Burn-in is not customarily performed on non-aerospace capacitors. Failure rate data are the basis of reliability level predictions for established,"high reliability" parts. These manufactured components are then "derated" to achieve a specific level of reliability. Accelerated life factors have been estimated for most types of capacitors. These data are not readily available for high voltage capacitors because very few high voltage capacitors are built to military specifications.

The relationship of failure rate to voltage and temperature can be expressed as:

$$\lambda\mu = \lambda r \, k^{(Tu + Tr)} \left(\frac{Vu}{Vr}\right)^{n}$$

where:

$\lambda\mu$ = failure rate at use conditions
λr = failure rate at rated conditions
k = temperature acceleration constant
Tu = use temperature (^{o}C)
Tr = rated temperature (^{o}C)
Vu = use voltage
Vr = rated voltage
n = voltage acceleration factor

The following are values of constants k and n for some common dielectrics:

TABLE 23
CAPACITOR DIELECTRICS

	k		n	
Dielectric	DC	AC	DC	AC
Mineral oil-paper	1.07	1.036	5	5
Askarel-Paper	-	1.09	5	5.6
MYLAR	1.07	-	5-7	-

Published data that relate voltage to dielectric thickness for a given life-time are always based on some specified active area of dielectric. This voltage must be derated by a factor that depends on the ratios of the active area of the capacitor being designed and the active area of the test sample (Figure 71).

5.2.3.7 Checklist of Significant Characteristics. To select the most appropriate capacitor for a particular application, the characteristics shown in Table 24 should be considered in relation to application requirements in the interest of attaining the optimum balance of producibility, performance, and cost.

TABLE 24

FACTORS AFFECTING CAPACITOR SELECTION

CAPACITANCE
- Rated value
- Tolerance
- Retrace
- Effect of:
  - Temperature
  - Voltage
  - Age
  - Pressure
  - Frequency

VOLTAGE RATING
- DC continuous
- DC transient
- Polarity
- AC low frequency
- AC high frequency, RF

TEMPERATURE CAPABILITY

DISSIPATION FACTOR OR Q
- Power factor
- Equivalent series R
  - Effect of:
    - Temperature
    - Voltage
    - Frequency
    - Capacitance

LEAKAGE CURRENT OR INSULATION RESISTANCE
- Effect of:
  - Temperature
  - Polarity
  - Age
  - Voltage

STRAY CAPACITANCE AND RESISTANCE TO CASE

IMPEDANCE
- Effect of:
  - Frequency
  - Series R
  - Series X_L

RIPPLE/PULSE CURRENT

FAILURE RATE
- Effect of:
  - Voltage
  - Temperature
  - Ripple current
  - Transients

FAILURE MODES

NOISE

VOLUME & WEIGHT PER uF VOLT OR PER KVAR

MECHANICAL FEATURES
- Enclosure
- Mounting provisions
- Seal
- Flammability
- Effect of.
  - Orientation
  - Vibration
  - Shock
  - Humidity

COST

AVAILABILITY

5.2.3.8 Application. High voltage and low voltage capacitors are required for high voltage power supplies. Electrolytic, film-wound (unimpregnated), and ceramic capacitors are used for low voltage applications. High voltage applications use impregnated film and reconstructed mica. These capacitors have proven performance for filters. Ceramic capacitors have excellent properties for voltage multipliers.

One of the most frequent errors made by electronic designers is to base their designs on data taken at one frequency and temperature and then operate under a different set of conditions. Most failures probably are caused by such misapplications of data. A large amount of data are available today, but some are of indistinct origin or based on samples that no longer represent the material available. In addition, variations in testing procedures make comparisons difficult. Therefore, it is necessary to have a compilation of the most important dielectric and metal film characteristics for the capacitors in use.

As an example, many ceramic capacitors have been designed to operate at 60 Hz. Unfortunately, there is no simple relationship between the 60 Hz values and the values at high frequencies for dielectric constant and dissipation. Usually, as the frequency increases the loss characteristic becomes increasingly important because the resulting higher temperature affects the breakdown process. As a general rule, the lower the loss factor at a given frequency and temperature, the more likely the materials are to have a high dielectric strength.

In most ceramic applications the metal plates are bonded to the ceramic wafer. The relationship between the thermal expansion coefficients of the metal and ceramic often determine the success of the capacitor. The expansion coefficients need not be identical but they must be well matched for optimum results. For instance, kovar and nickel are a much better match than silver or aluminum for berryllia or magnesia ceramics.

5.2.3.9 Testing. Dc partial discharge testing at the NASA Goddard Spacecraft Center has shown that correlating the dc ramp corona test method with scanning electron microscope (SEM) photography can identify many internal flaws in $BaTiO_2$ capacitors. These capacitors were for dc applications of single-layer and multilayer disc construction. These capacitors passed all burn-in, characteristic, dielectric withstanding voltage, and other screening tests, except the ramp dc test. By using this test a pass-fail criterion could be established to discard inadequate pieceparts.

The physical sizes of capacitors make them difficult to test at high voltage. Usually they must be tested when immersed in a liquid or pressurized gas. Liquid is preferred because it does not penetrate the pores and conceal hidden flaws as pressurized gas does. It is essential to ensure that the burn-in process does not include silicone oil. Silicone oil will make it almost impossible to obtain an adequate bond with epoxy or polyurethane encapsulants and some silicone products.

High-frequency capacitors used in high-frequency power supplies must have low inductance and very rapid charge and discharge characteristics. To obtain these goals, design and materials engineers look for better packaging and improved field enhancement at the foil edges, as well as higher dielectric strength materials. One application has the capacitor case biased to 25 percent of the working voltage to relieve the stress on the outer foil and negative lead. To decrease capacitor weight some designers are working on plastic cases. Important features in capacitor design and fabrication are:

- Obtaining a void-free homogeneous film. Many thin films have up to 10 percent variation in thickness and one or more pin holes per square meter.
- Controlling the foil edges. A sheared edge or square edge has very high field stress at the corner. Depending on the film thickness, the field at the edges of a sheared edge may be four to five times that across the body of the foil (Figure 73).

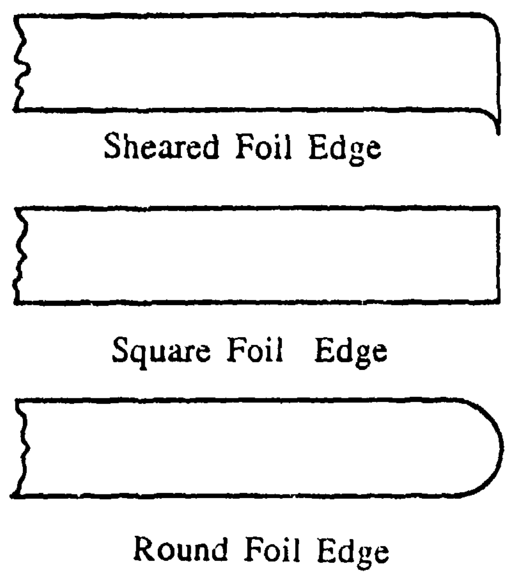


Figure 73. Capacitor Foil Edges

- Eliminating dirt and debris within the capacitors during construction (rolling of the foil)
- Eliminating voids between the capacitor plates or wrinkled film or foil, which will enhance breakdown.
- Use better high dielectric strength films.
- Determining the frequency spectrum of each film material as a function of temperature. A polarization at a critical pulse frequency will cause heating and loss of the dielectric. The frequency spectrum should be measured through 100 MHz.
- Designing for low inductance. This will result from short leads.
- Specify processes that result in an excellent bond between the foil and lead caps. A high-resistance joint will result in overheating and capacitor failure.
- Conducting tradeoffs between large, reliable capacitors and lightweight new designs. Doubling the number of lightweight capacitors to meet reliability values is a poor design practice when 20 percent more weight and volume for a single unit can achieve the same goal.

In an attempt to enhance the file at the foil edges T. E. Springer et al. (Reference 136), suggests adding a small round wire of the same diameter as the thickness of a square-ended foil. At first this appears to be a logical solution to the field problem, but it has the drawback of air (gas) voids existing between the foil and wire. The field at the corner would still be great enough to generate partial discharges and to damage the insulation system (Figure 74).

High-energy-density capacitors have been developed and evaluated by American manufacturers (Reference 137). Films of mylar and polyvinylidene fluoride (K-F polymer) were used in the construction with impregnates of silicone oil, castor oil, and MIPB; other impregnates are shown in Table 23 with the construction and design parameters shown in Table 25. Test results indicated that the K-F polymer with silicone oil impregnate provided the best results. Edge effects were rare when the winding tension was moderate. MIPB and K-F polymers were less attractive but have excellent radiation resistance, a feature that must not be overlooked in many applications. Some newly

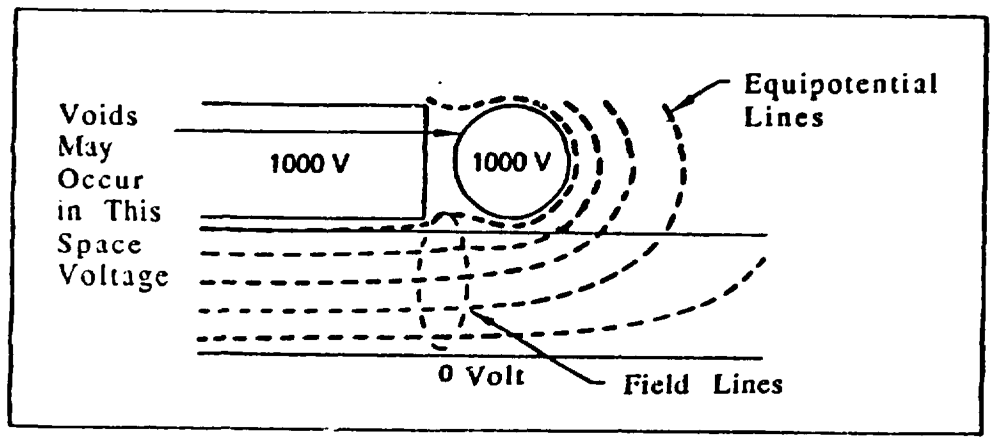


Figure 74. Equipotentials and Maximum Field for Foil With Guard Wire

TABLE 25

PREVIOUS DEVELOPMENT PROGRAMS ON HIGH DENSITY CAPACITORS

Capacitor	Construction	Major Design Parameters
A	Mylar/MIPB	All film vacuum environment, large temperature range
B	K-F/Paper/ Castor Oil	Vacuum, large temperature range
C	Mylar/Silicone Oil	All film
D	Mylar/MIPB	All film, vacuum, large temperature range
E	K-F polymer/ Silicone Oil	Vacuum, large temperature range
	K-F polymer/ MIPB	All film

developed molecular polymers are being researched. These polymers, when fully developed, may increase considerably both the energy capacity and high voltage capability.

Many HV capacitors designed for small power supply applications have non-metallic cases. Some of these capacitors have excellent film-plate construction but less than desired end caps. In some cases the end caps have very sharp edges which can lead to high field stress; therefore, a small modification is recommended. Corona shields should be designed so they can be placed over the high voltage ends of the capacitors, as shown in Figure 75. The leads should be bent to penetrate through the center of the shields and soldered to make them a part of the design. The high voltage leads can then be soldered to a more centralized location on the corona shield to improve the stress levels. This modification will greatly reduce the maximum field stress between the ends of the capacitor and another part or ground. It must also be remembered that a sharp point also results in a thermal short circuit. Better thermal control can be achieved by using the corona shields.

5.2.4 Magnetic Devices. Motors, generators, transformers, and inductors are magnetic devices that require electrical insulation between turns of the coils, between coil layers, between adjacent coils, and between coils and associated parts such as the magnetic cores and structure.

The coil insulation in high voltage rotating machines may be subjected to gaseous ionization or corona discharge during proof testing and in service. These partial discharges may occur externally from the windings to the metal frame or cores, and internally in voids or crevices in the insulation. Analyses of electrical failures in high voltage magnetic devices have revealed erosion in the largest cavities of nonhomogeneous insulation. These larger cavities may have developed initially by thermal aging, mechanical forces, or by partial discharge attack. A combination of these degrading effects is most likely.

The erosion or weakening of insulation through internal discharge attack may be the result of several effects progressing simultaneously:

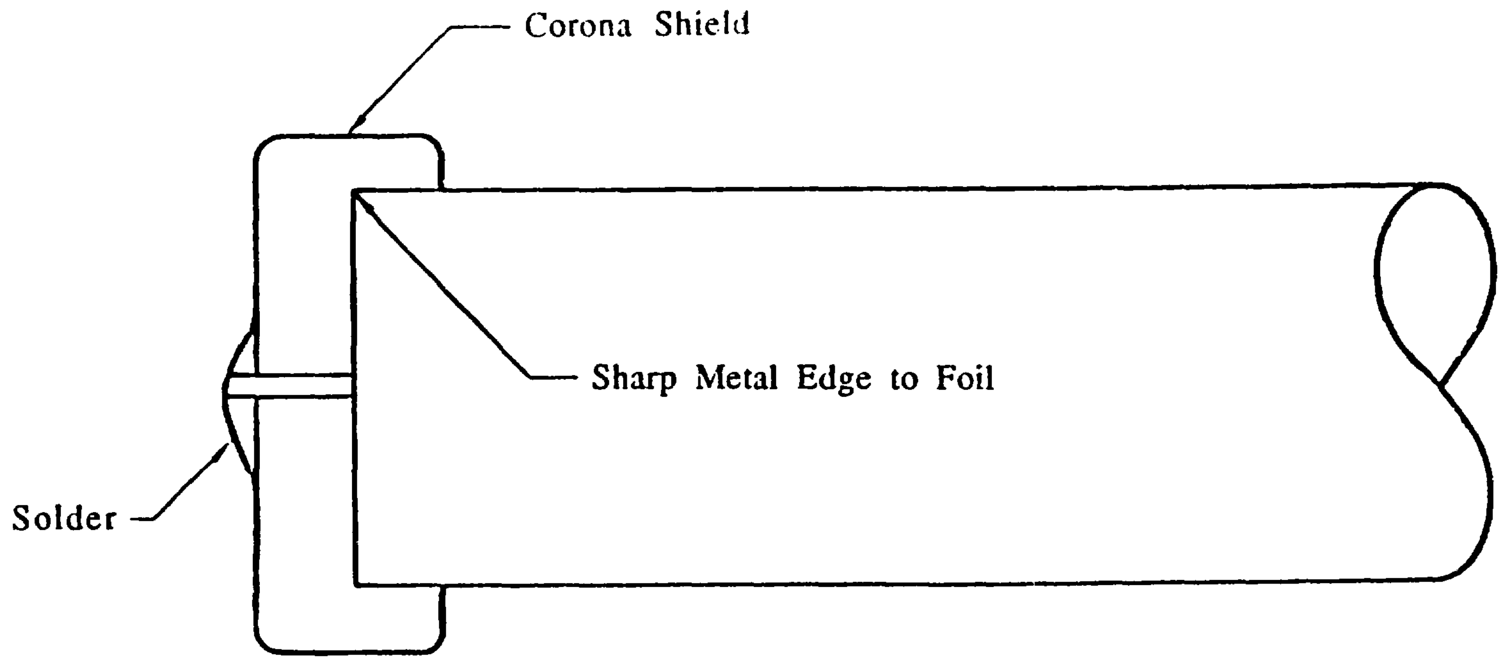


Figure 75. Corona Shields Over Capacitor Ends

- Thermal degradation caused by local heating from ionization streamers and increased losses in surrounding solid materials
- Degradation of solid material and reaction with the gas in the cavity
- Degradation of the gas and reaction with the cavity surfaces
- Partial breakdown in solid material (treeing)

5.2.4.1 Transformers. High voltage pulse transformers and inductors that must withstand continuous pulses have special requirements. Cast solids, liquid with films, and gases with films are used in the insulation system between turns, between windings, and between turns or windings and the core or case. The breakdown of one insulation usually results in an instantaneous breakdown of a multidielectric system, where breakdown results from overstressing the materials, or partial discharges. Experiments by Kao and McMath (Reference 138) indicate that a liquid-solid (film) dielectric system used in a pulsed voltage application has a time-dependent breakdown strength in the range of 10^{-6}s to 10^{-9}s. They also showed that the dielectric strength of transformer oils and n-hexane are decreased by a factor of three for an increased pulse voltage rate of rise in the range of 10^2 to 10^4 kV/μs.

Pulse breakdown data for gases, liquids, and solids are treated in Volume IV of Reference 118. To keep within the design limits for the pulse transformer, the maximum electric field stress must be calculated and designed so as not to exceed the average dielectric stress by a factor greater than 3.

A simple spiral wound transformer (Reference 139) is shown in Figure 76 and its equivalent circuit in Figure 77. There are two things to note about this circuit:

a. The insulation capacitance and coil inductance may form a resonant circuit if the components are incorrectly designed. This will greatly increase the field stress in the insulation circuit.

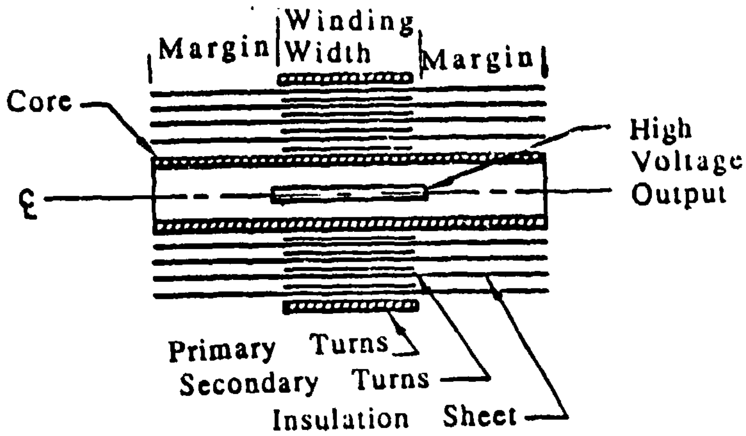


Figure 76. Simple Spiral Strip Transformer

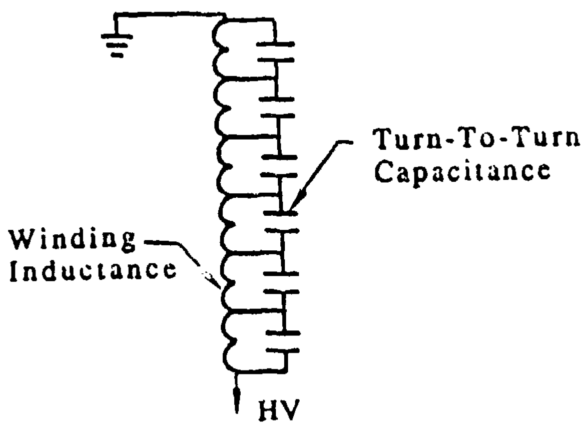


Figure 77. Equivalent Circuit Through the Thickness of a Spiral Strip Winding

b. The capacitive circuit acts as a voltage divider when the pulse transformer has an induced pulse injected. High-energy externally induced pulses may exceed the capacity limits of initial high voltage turns of the circuit.

5.2.4.2 Insulation System. When the transformer or coil design is complete, the insulating system materials must be selected. Two important encapsulating materials characteristics that must be met are wetability and thermal compatibility. Wetability is the capability of a material to wet, fill, and bond to all surfaces regardless of its shape, density, or composition. For instance, very few materials wet and bond to Teflon surfaces. Polyester mats and some nylon composition mats have excellent wetability and fill; the polyesters being superior to the nylon compositions.

5.2.4.3 Encapsulation. Several manufacturers produce epoxy, polyurethane, and silicone dielectric materials that have been used successfully for encapsulating aerospace magnetic devices. Some of these materials have restrictions; for example, a minimum operating temperature of -20°C. A material in a particular application may have worked well without restriction but the same material in a new application in a different environment may require restrictions. Scotchcast 280 and 281 are examples. In a large transformer wound with AWG 24 wire, filled Scotchcast 281 was found to be the better product. The filler was fine enough to pass through the winding interspaces, completely filling the coil winding. The coil winding dimensions were 25 cm in diameter, 2.5 cm thick, and 10 cm high. The coefficient of thermal expansion of the coils was a reasonable match with the Scotchcast 281, and no cracks or voids developed during temperature cycling between -40° and +85°C.

Another coil, designed for a higher voltage but lower current, was wound with AWG 32 wire, but the inner windings were not totally impregnated with Scotchcast 281, even after a vacuum treatment followed by nitrogen pressurization at five atmospheres. In a redesign the coils were impregnated with Scotchcast 280, and overcoated with Scotchcast 281. This led to difficulties. During removal from the mold, a grease film and dirt were

deposited on the Scotchcast 280 by handling. The grease and dirt left the two materials poorly bonded. Resulting cracks and voids contributed to high partial discharge counts in a subsequent corona test. Incidentally, controlled introduction of additives between layers of a dielectric is a method of acquiring voids and cracks for testing to confirm theoretical models.

Some insulations show excellent bonding to glass test tubes for large temperature extremes, but fail when used as a circuit encapsulation. Some materials may separate at the bond when applied to electrical parts; for example, silicone on epoxy materials and acid-based silicone on water-based silicones. Occasionally a material will not harden when in a sealed evacuated container. Some materials may also have bonding problems when subjected to thermal cycling; that is, the insulation will crack or delaminate when cooled to temperatures less than -20°C. Table 26 shows low-temperature performance of some of the dielectrics that are useful for magnetic devices.

Although vacuum encapsulation followed by overpressure is used extensively for encapsulating parts and components, pressure extrusion is equally acceptable. The success of the encapsulation process depends on the cleanliness, experimental process development for the encapsulated part or component, the workmanship, and post-cure handling before and during connection into a higher order electronic unit.

5.2.4.4 Life. Transformer insulation life is based on two factors--overstress and time. Overstress must include two factors: the turn-to-turn overstress within the winding and the impressed input/output voltage magnitudes. An example is a 50 percent overvoltage 1 µs transient. For many transformer designs, most of the transient overvoltage will appear across the initial turns of the winding. This could momentarily triple the stress between turns and/or between the turns in the affected layer to its adjacent layer. This type of overstress can cause puncture to occur between the inner or outer layers of a transformer designed with high voltage stresses. At first, it would be expected that the failure would occur between the end turns. The failure will occur in the vicinity of least insulation; insulation flaws such as voids, or places where impurities are embedded in the insulation. Thus, the breakdown could occur

TABLE 26

PERFORMANCE OF INSULATING MATERIALS AT LOW TEMPERATURES AND 10^{-4} Pa PRESSURE

Material	Voltage	Temperature	Comments
PR 1538	600 Vrms	-40°C	Cracked. No damage - low voltage in vacuum
Solithane 113/300 Formula 12	15 kV	-85° C	Successful
Scotchcast 280/281	400 V_p	-55 to 85°C	Very thin coat Transformer okay
RTV 615	15 kV	-55 to 85°C	Cracked
6154	15 kV	-20 to 85°C	Successful
DC 3110	4 kv	-36 to 50°C	Cracks appeared
	4 kV	-18 to 50°C	Successful
PC 22	1.0 kV	-30 to 70°C	Successful
DC 3110 DC 1201 Primer	18 kV	-55 to 70°C	Opaque material
Silastic E	20 kV	-55 to 85°C	Successful
Conap 2521	20 kV	-55 to 85°C	Successful
Stycast 2651 (filled)	8 kV	-55 to 85°C	Successful
Sytcast 2850	10 kV	-55 to 85°C	Successful

in the center of the winding. Pulse transformers and very high frequency transformers are less prone to this type of failure.

5.2.5 Mounts, Interconnects, and Surfaces. One rule that all high voltage designers should follow is that a good high voltage mount, surface, termination, and ground surface should have smooth rounded structure. Decreasing the maximum electric field stresses is the first step in a good thermal design. It is as important for the solid dielectric surfaces of components and parts to be rounded as it is for the metallic surfaces. Any change in dielectric constant in an insulating system is affected by the interface smoothness and roundness. Some configuration ideas follow.

5.2.5.1 Terminal Boards and Supports. Composite and laminated insulation may be used for terminal boards, and also for supports that separate the coils and wires from the cores, structure, and containers. Some electrical and mechanical properties of glass and nylon containing laminates are shown in Table 27. A more complete list of materials and properties can be found in References 140 and 141.

A terminal board for high potential should always be made from qualified insulation. The board may be flat if the voltage is less than 20 kV, provided the electrical stress is:

- Less than 10 volts/mil for long life (10 to 30 years)
- Less than 10 to 25 volts/mil for short life (1 month to 1 year) with treated boards. In a dry, clean, atmosphere of pure gas these values can be increased by about a factor of 3.

Terminal boards operating at voltages greater than 20 kV should be contoured to increase the creepage paths. Three basic methods of contouring are:

TABLE 27

PROPERTIES OF LAMINATES AND COMPOSITIONS

Material Properties

NEMA Grade	Base Material	Resin	Specific Gravity	Water % Adsorbtion
G-7	Glass cloth	Silicone	1.68	0.55
G-9	Glass cloth	Melamine	1.9	0.8
G-10	Glass cloth	Epoxy	1.75	0.25
G-11	Glass cloth	Epoxy	1.75	0.25
N-1	Nylon	Phenolic	1.15	0.6
FR-4	Glass	Epoxy	1.73	0.25
FR-5	Glass	Epoxy	1.75	0.25

Mechanical Properties

	Flexural Strength $N \cdot m^2 \times 10^8$ 1.6mm thick	Tensile Strength $N/m^2 \times 19^8$	Compressive Strength $N/m^2 \times 10^8$	Bond Strength kg	Rockwell Hardness M-scale
G-7	1.4	1.6	3.1	295	100
G-9	4.1	2.7	4.5	770	---
G-10	4.1	2.4	4.8	900	110
G-11	4.1	2.4	4.8	725	110
N-1	0.7	0.6	1.9	450	105
FR-4	4.1	2.4	4.8	900	110
FR-5	4.1	2.4	4.8	725	110

Electrical Properties

	Dielectric Constant 1 MHz 0.8mm	Dissipation Factor 1 MHz 0.8mm	Dielectric Strength Kv/mm (0.8mm)	Resistivity: Volume Resistivity OHM-Cm	Resistivity: Surface Resistance Megohms	Arc Resistance Sec.
G-7	4.[illegible]	0.003	11	--	--	180
G-9	7.5	0.018	10	--	--	180
G-10	5.2	0.025	20	10^{12}	10^4	128
G-11	5.2	0.025	16	10^{12}	10^4	115
N-1	3.9	0.038	15			
FR-4	5.2	0.025	18	10^{12}	10^4	128
FR-5	5.2	0.025	18	10^{12}	10^4	128

- Cutting slots (gas-filled regions) between the terminals
- Building barrier strips between the terminals
- Mounting the terminals on insulated standoffs

These three methods are shown in Figure 78. A combination of the three methods may be necessary for voltages greater than 100 kV. The slots in a slotted board form creepage paths and flashover barriers on both sides of the board. A board with barriers is the most difficult to design. The barriers must be built on both sides of the board, and the board has to be made from materials that will not form creepage paths under the barriers, or in laminated boards, through the board laminates. The barriers must not interfere with the terminals or the wiring.

Insulated standoffs are a form of barrier strips. They are difficult to design because they must withstand the forces applied by the terminals, and the terminal anchor must be embedded in the top surface of the standoff. The anchor must be contoured for minimum electrical stress.

5.2.5.2 High Voltage Leads. Leads between high voltage parts should be made of round, smooth-surfaced polished metal tubing. Steel and nickel-plated metals are preferred, but other softer metals are often used because they are easier to fabricate. The radius of curvature on all bends should be at least 2.5 times the conductor diameter to avoid flattening or crushing the tube at the bend. The ends of the tubes should be flattened as little as possible, but this becomes difficult for pieces other than straight sections. When the end of the tubing is flattened, the corona suppression shield should extend over the edges of the flattened end, as shown in Figure 79. Ample space must be provided between the inside surface of the insulator and the metal tube. A safe design would be based on the assumption that the full voltage stress exists on the top edge of the bushing.

Hollow tubing must be vented. Vent holes should be drilled through one wall of the tubing at both ends. The vent hole should face the corona shield. No other holes should be drilled in the tubing.

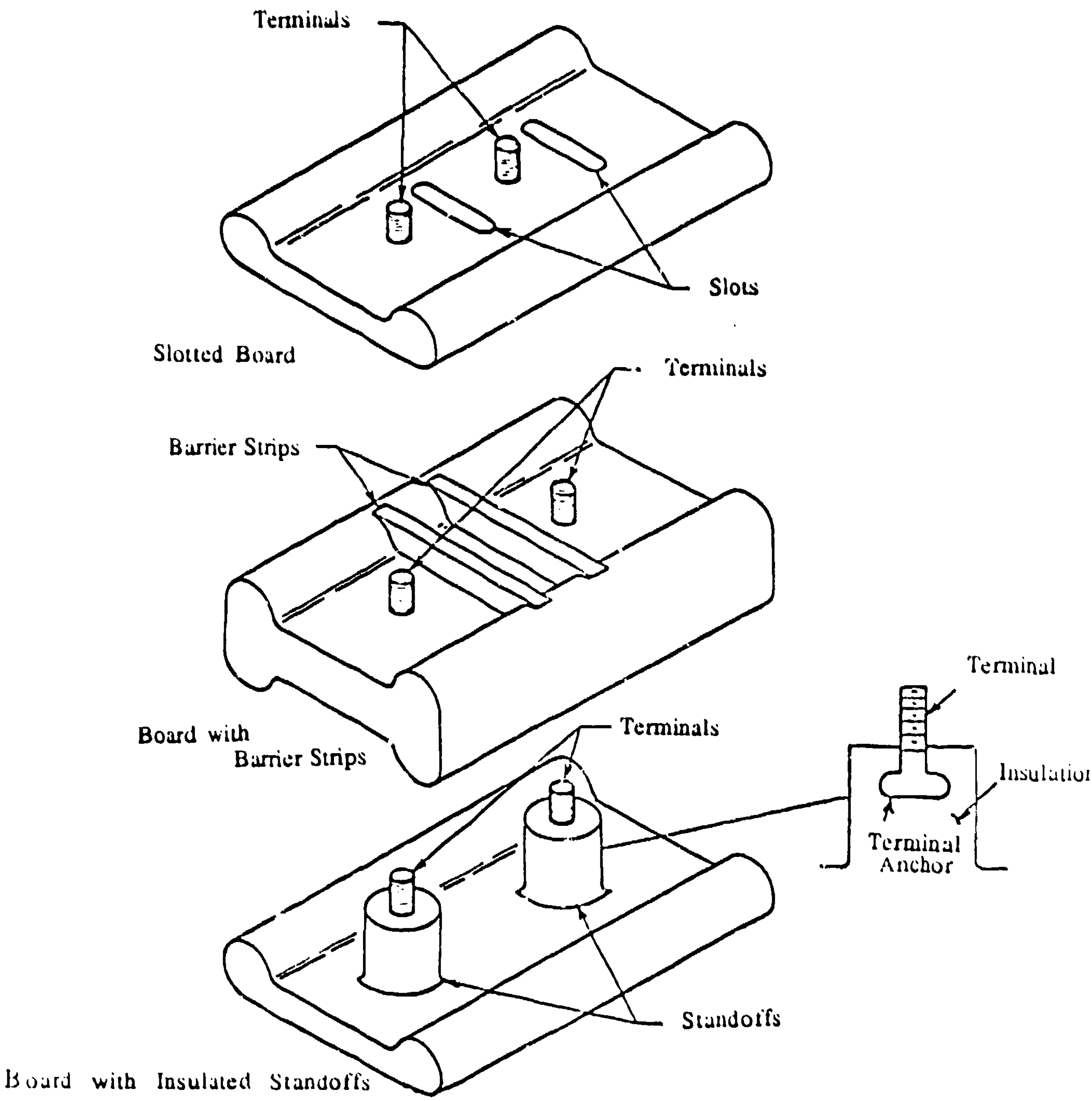


Figure 78. Terminal Boards

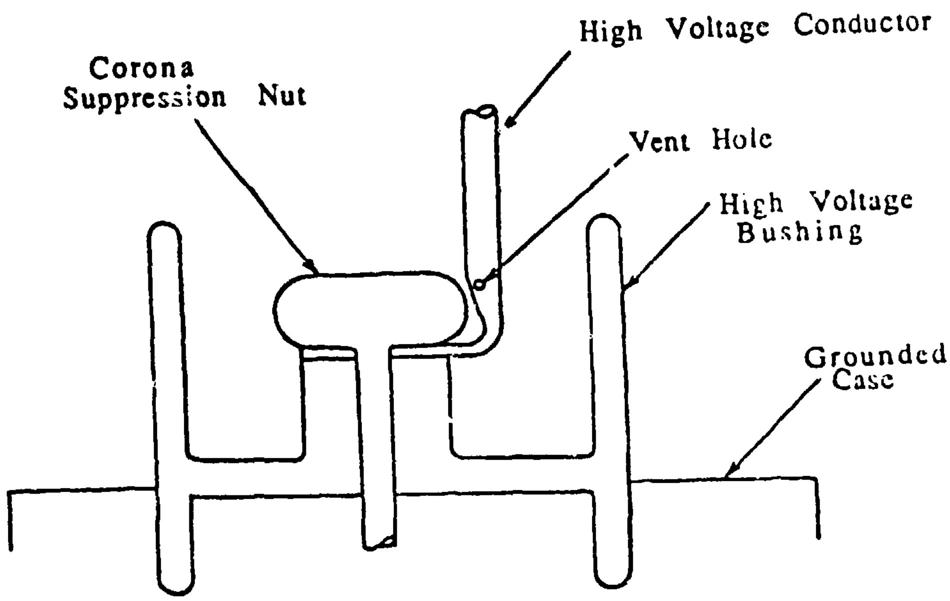


Figure 79. High Voltage Lead and Bushing

5.2.5.3 Lead Terminals. High voltage flexible lead termination should be designed to eliminate pressure points on the terminal board (Figure 80). Pressure points will cause delamination, which enhances internal tracking. Also, the terminal should be protected with a corona ball or shield.

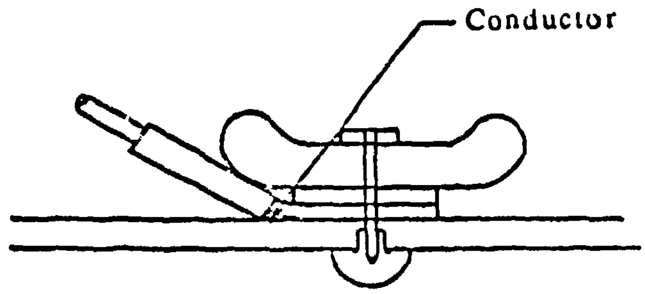
Other insulation techniques include either burnishing or enameling over the knots in ties. Otherwise, the feathered ends will become points from which corona discharges can emanate (Figure 81).

Small pieces of insulation must be cleaned out of the transformer case. Otherwise the "chips" may lodge in the field between a coil and metal and cause corona, which will contaminate the gas or oil insulation. Wire terminations should be designed and installed so the field approaches that of a parallel plate configuration without point discontinuities.

Encapsulated coils and coil supports should have rounded corners (Figure 82). Rounding the corners eliminates high stress points or low utilization factors in the media between the encapsulated coil and its support, frame, or adjacent coil.

5.2.5.4 Solid State and Vacuum Parts. Sometimes in aircraft installations, live high voltage circuits must be switched. Devices used to switch aircraft high voltage are hard-vacuum tubes, hydrogen thyratrons, silicon-controlled rectifiers (SCR), and vacuum switches. Associated with these components are resistors, capacitors, wiring, magnetic devices, isolating transformers, electro-optical isolators, and triggering circuits. A device sometimes used in high voltage circuits is the crowbar switch, which very quickly shunts high voltage conductors with a resistor to harmlessly discharge energy storage capacitors. This crowbar action prevents a damaging dissipation of energy into a fault.

High voltage circuit components protected by a crowbar circuit may be subjected to large voltage transients and excursions preceding and during faulting. These transient voltages may be either negative or positive and more than double the normal circuit voltage. In addition, high frequency voltage



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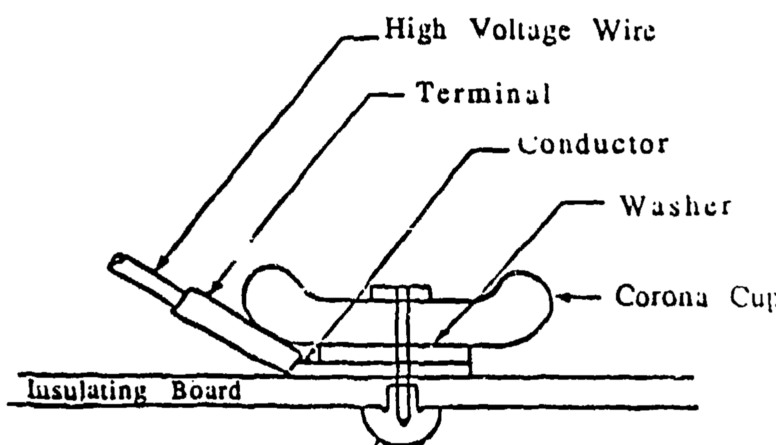

PROPER

Figure 80. High Voltage Terminals

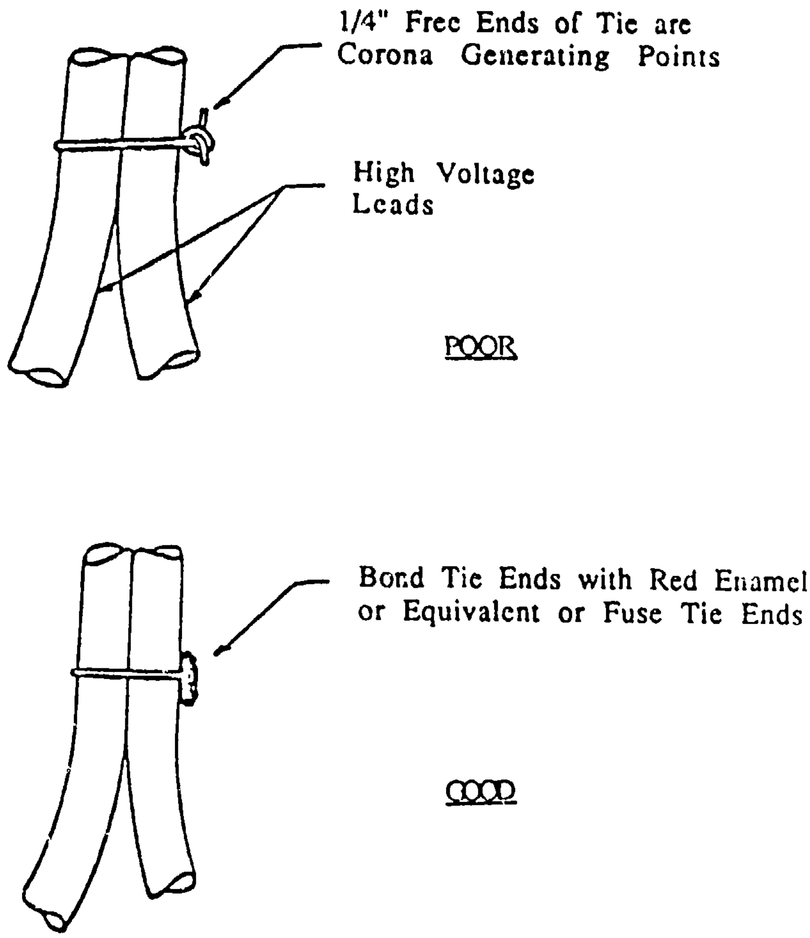

Figure 81. High Voltage Ties

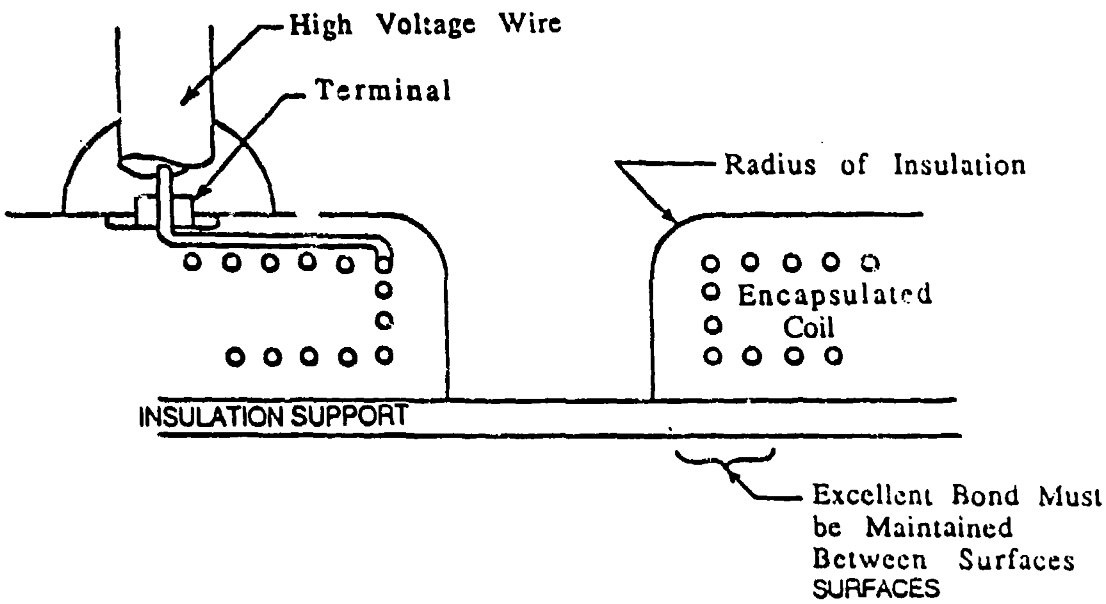

Figure 82. Round Corners on Encapsulated Coils

components are likely to be present. The insulating surfaces and thicknesses must be capable of withstanding multiple crowbar actions. Boards, terminals, bushings, and other insulation must be impulse tested to show capability for withstanding at least 100 to 500 impulses due to crowbar action.

Solid-state devices are referred to as "chips." That is, the actual solid-state device has very sharp corners, is very small, and may be made of a multitude of chips. This implies that, before potting, the assembled arrangement may appear as a group of needle points or razor sharp edges. When coated all these sharp points and edges are hidden, but the fields remain to emanate from the surface of the coating. These fields must be considered. The fields exist, and the problem is what are the dielectric properties of the coating material. A high dielectric constant coating material reduces the maximum field stress next to the chip within the coating. This implies that if an encapsulating material is selected with much lower dielectric constant, the coating material has little voltage drop, and a large voltage drop will exist at the insulation interface. Thus, the engineer must obtain the dielectric properties of the coating material and its thickness over the chip or multichip internal construction before recommending an insulation thickness for the solid-state device.

5.2.5.5 Circuits. The high voltage insulation design starts with a circuit diagram showing all parts and their anticipated design voltage levels. The parts are then arranged in a preliminary package which minimizes the net voltage between parts and voltage drop across each part. In designing high voltage assemblies, it is important to avoid wire and part crossovers that put a low voltage surface on one part next to a very high voltage surface of another part. Circuits containing resistive or capacitive voltage dividers require careful design, especially if the resistor or resistor string is extended. For example, a resistor or group of resistors may form a voltage divider between the high voltage terminal and local ground. The normal plan is to zigzag many resistors from the high voltage terminal to the ground terminal, or to have one resistor with one end attached to the high voltage terminal and the other end grounded. Sometimes other high voltage parts near the center of the resistor or resistor chain may be at full voltage or at ground potential,

stressing a zone that is not normally designed for voltage stress. This is poor design practice and must be avoided.

5.2.5.6 Taps and Plates. A high voltage rectifier is normally assembled from a series of connected diodes. Occasionally, a voltage tap is required at the center of the diode string. This tap should be made of material having the same diameter as the diode surface, and be thick enough for attachment of a round tubular connection. Soldered joints should not be used because most solder electrodes have lower breakdown potentials than metals such as steel, nickel, brass, copper, and aluminum.

A potential shaping surface within a stack of series-connected diodes can be a thin plate of metal provided with a large-radius edge as shown in Figure 83. This curved edge suppresses corona.

5.2.5.7 Control Wiring. High voltage units may use circulating pressurized gas both for cooling and as part of the insulation system.

Electrically controlled switches may also be required for system voltage regulation and performance measurement. These functions are performed with components such as fan motors, relays, motor-driven switches, instrumentation, sensors, and circuits that operate at voltages less than 250 volts rms or dc. These devices and circuits, normally insulated, are incapable of withstanding the induced transient voltages coupled into them by high voltage faults, crowbar action, and high voltage start-stop sequences. Therefore, these circuits and their wiring must be well shielded.

Low voltage devices and their wiring must be well separated from the high voltage circuits. Low voltage conductor shielding has rough surfaces that look like multiple points that enhance field gradients with respect to the high voltage. This will result in lowering the breakdown voltage between high voltage parts, or conductors, and the low voltage shields.

Shielding the low voltage components and wiring should be adequate to hold the induced impulses to less than 750 volts peak in common-mode and

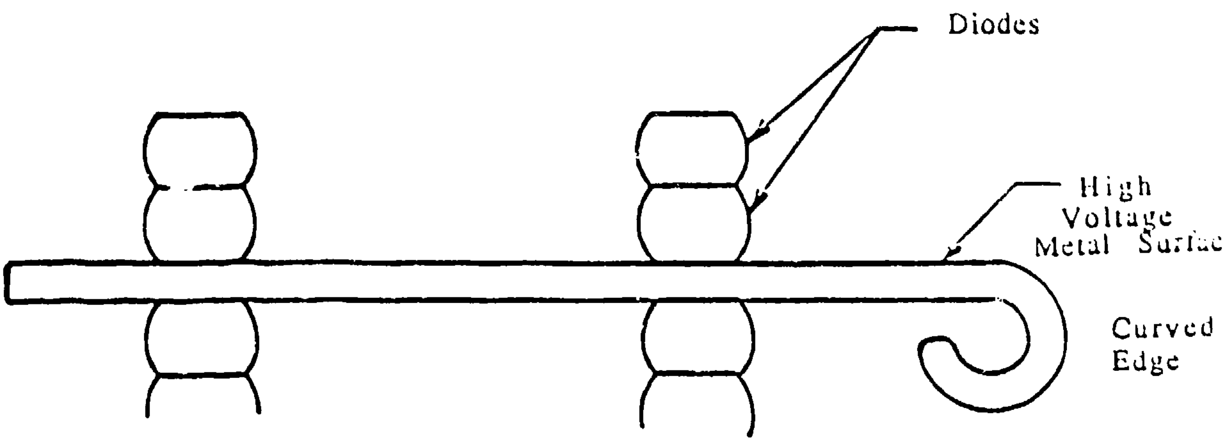

Figure 83. Curved Edge on High Voltage Plate

differential-mode circuits, and to less than 7500 volts peak in the wiring. These limits will prevent destruction of most hardened solid-state devices, inductors, capacitors, and resistors that are commonly used in the control circuits. Many circuits have been evaluated for damage or malfunction by electromagnetic pulses. Some of these data were compiled in Reference 142.

5.2.5.8 Insulated High Voltage Wiring. A designer may have to interconnect two or more components with a high voltage flexible wire that has insulation inadequate to sustain the full electrical stress of the applied voltage. This can be done if:

a. The diameter of the wire is increased with more insulation. With dc voltage stress, the low resistance of the insulation and near infinite resistance of the gas allows the surface of the wire insulation to charge to the conductor voltage level. This larger diameter lowers the voltage gradient in the highly stressed gas next to the conductor. With ac, the voltage at the surface of the wire is determined by the configuration and dielectric constants of the wire insulation and gas space.

b. Adequate and rigidly controlled spacing is provided between the wire and ground planes.

Generally, extra-flexible wire should be used only when the bending and placement of the tubing through the high voltage volume is too difficult or will mechanically stress parts during installation. Terminations on extra-flexible wire will not stay in place as they will with solid tubing. Therefore, the terminations must either be keyed to a slot in the insulation barrier, or a special locking device must be developed for the termination and/or wire end.

5.2.5.9 Printed Circuit Boards. High voltage printed circuit boards must be designed to withstand high voltage transients and fields. High voltage terminals may be mounted on kel-F (a fluorocarbon material) stakes or epoxy molded standoffs to separate the voltages, as shown in Figure 84. If adequate

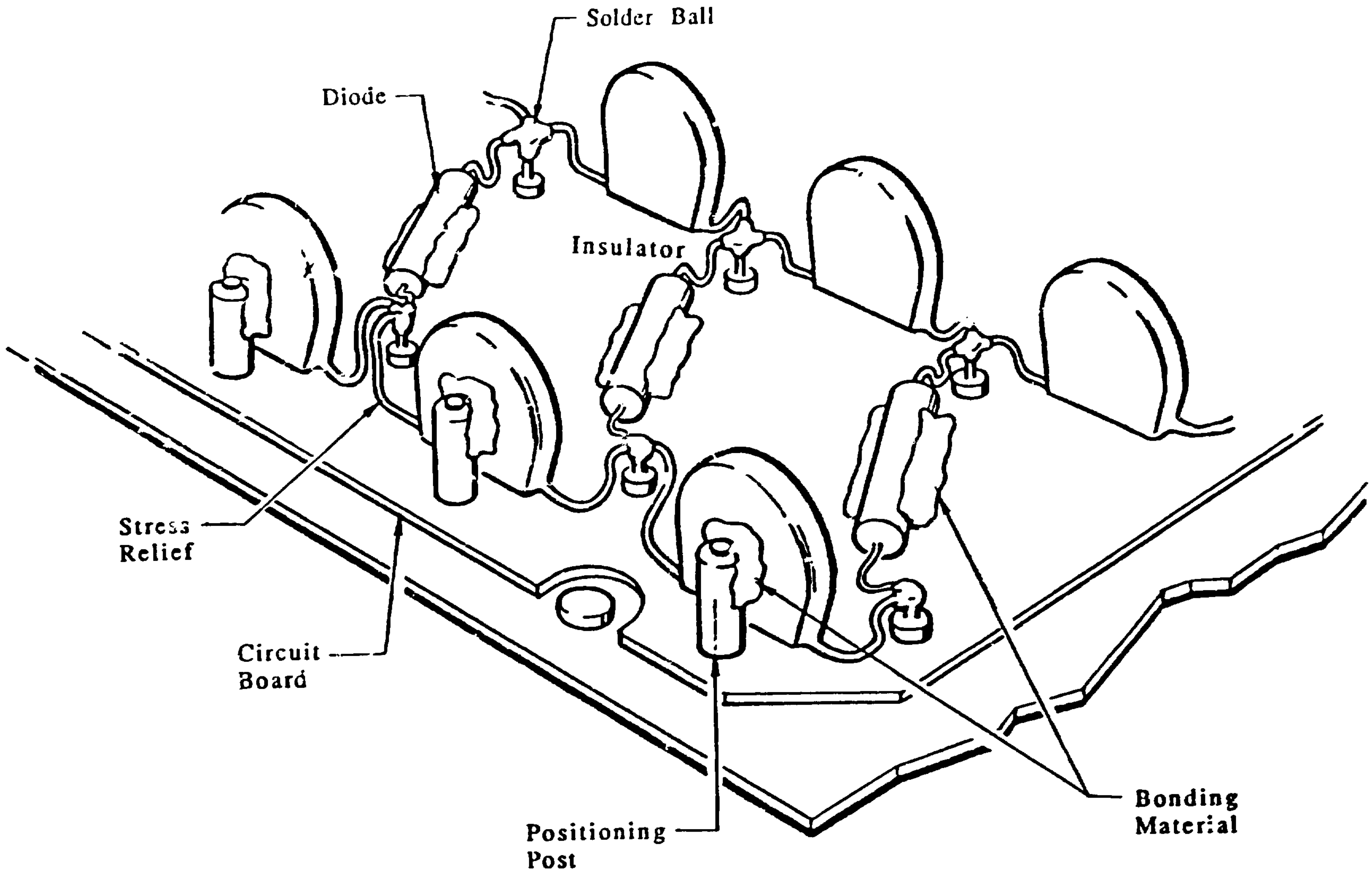

Figure 84. High Voltage Circuit Board

creepage paths are not provided, surface arcs will occur in time. These creepage paths can be inhibited by cutting slots in the board to break up the fields. A field plot is recommended to determine the optimum placement of the slots. Note that the slots may be curved or L-shaped to inhibit some field paths. Board selection is very important. Fiberglass resin-filled boards are used extensively. Some of the boards tend to delaminate when subjected to excessive pressure. Creepage paths will grow within the cracks and cause a board/circuit failure. Some boards are made successfully of velspar and other solid materials (Reference 94). The advantage of this construction is that these materials can be machined to increase creepage paths. In addition, their surface resistivities are very high. Conformal coating materials must be evaluated for compatibility with each material used for construction and for parts coatings.

5.3 Transients. In spacecraft design, the peak voltages from pulses and transients must be calculated and the equipment must be designed to withstand the peak voltages. Transients with peak values to 160 percent have been recorded on radar power supply output lines following a modulator tube arcover of a crowbar action. Systems employing pulses, short-circuiting devices, and vacuum tubes subject to arcover may be subjected to these peak pulses.

Other sources of transients are high voltage transformers and circuits having an abundance of partial discharges with peak values exceeding 100 picocoulombs. The compact design dictates that low voltage and high voltage circuits be installed in the same module with little spacing. Transients or partial discharges generated within the voids and air spaces in the high voltage winding are coupled into the low voltage circuitry by capacitive coupling though the insulation between conductors and circuit components or by common mode through the ground circuit. High-speed bidirectional transient voltage suppressors may be placed on the low voltage windings of the two transformers to protect the low voltage circuits. These suppressors may be placed in one of two locations: either at the source of the voltage transient (at the transformers), or near the parts they are designed to protect.

5.3.1 Identifying Conducted Electromagnetic Interference (EMI) Sources. There are two primary areas within the electronic circuits where EMI is generated: The ac-to-dc conversion package and switching circuitry (assuming switch mode conversion is implemented) and the transients and partial discharges within the high voltage circuitry. Some energy may be conducted to the low-voltage control/sensing integrated circuits (IC) by means of the control lines. This can cause controlling errors or, if severe enough, overstress the IC, resulting in permanent damage. EMI may also be conducted from the source or load back through the supply and then to the regulatory IC. This case must not be overlooked. Many times, especially in high voltage, momentary shorts occur across output terminals that have fast rise and fall times (less than 1 μs).

5.3.2 Limiting Conducted EMI Effects. When the sources of conducted EMI are known by tests and evaluation, calculations may be made as to their magnitude and location within the frequency-domain. This is accomplished by knowing maximum voltage and current levels used within the EMI sources, semiconductor rise time and fall time, and power supply input and switching frequencies. Many papers concerning these methods have been written detailing these calculations (Reference 143).

After EMI levels are established, techniques may be used to filter or suppress the EMI to acceptable levels that will not damage the low voltage controlling IC. (Reference 144) This must be done in such a manner that normal operation is unaffected.

5.3.3 Identifying Radiated EMI Sources. Radiated EMI comes in two forms; that is, it is produced from both E and H fields. E field radiation varies directly with the voltage of its source. H field radiation is dependent on current, number of turns, and the loop area of the current.

As in conducted EMI, radiated EMI is produced wherever switching and commutating circuitry are located. The interference sources extend into magnetic devices (transformers and inductors) that emit magnetic fields. Also, component leads, wiring, and printed circuit strips can all transmit EMI.

5.3.4 Limiting Radiated EMI Effects. In general, radiated EMI can cause erroneous compensation in power supply outputs because of bias level shifts in IC operational amplifiers and associated circuitry. Metallic shielding (Faraday shielding) of rectifiers, magnetics, and switching circuitry, reduces the EMI transmission (Reference 145). Controlling (slowing) transistor and diode risetimes and falltimes (snubbers) can reduce EMI generation (Reference 146). However, this can increase power dissipation within the supply, reducing efficiency and increasing heat sink requirements.

5.4 Grounding and Bonding. Plans exist for spacecraft with power requirements of a few watts to 2.5 MW. The bonding and grounding of these units will vary considerably. Smaller spacecraft with powered loads to 5 kW will use standard, single-point grounding techniques with the solar arrays referenced to the central load module. Larger spacecraft using multiple solar array sections capable of being transported to space via the shuttle and other transporting methods and assembled in space, may have a main load center and several remote load centers. Those spacecraft will require special bonding and grounding considerations.

5.4.1 Composite Structures. Spacecraft respond to the natural space environment by assuming a range of potentials relative to the plasma potential, depending on the plasma density, charged particle flux, and solar illumination. To equalize the potentials it is necessary to maintain continuous electrical paths throughout the structure. Present spacecraft with composite structure already use conducting coatings to alleviate the spacecraft charging problem with reasonable success. The use of a composite structure will change the nature of the spacecraft ground and complicate grounding procedures. Concerns such as electrical continuity through the structure will become more important whenever a composite joint is encountered; however, initial results with composite spacecraft have indicated that composite joint designs are workable when properly grounded and bonded. There is still a potential corrosion problem. The design criteria shown in Table 28 have been established for composite and metallic joints in spacecraft (References 147 and 148).

TABLE 28

RECOMMENDATIONS IN DESIGNS WHERE GRAPHITE/EPOXY IS COUPLED WITH OTHER MATERIALS, FOLLOW THE RULES BELOW:

METAL GROUPING

I	II	III	IV
Magnesium and Magnesium Alloys	Aluminum Alloys, Cadmium and Zinc Plate	Lead, Tin Bare Iron and Carbon or Low Alloy Steels	Cres. Nickel and Cobalt Based Alloys, Titanium, Copper, Brass, Chrome

- Do not couple Group I, II, or III Metals directly to graphite/epoxy.

- When Group I, II, or III metals are within 3 inches of graphite/epoxy and connected by an electrically conductive path through other structures, isolate* the graphite/epoxy surfaces and edges.

- Titanium, Cres (A286 or 300 series stainless steel), Nickel, and Cobalt-based alloys may be coupled to graphite/epoxy structures, when other Group IV metals are coupled, isolate* the graphite/epoxy surfaces and edges.

* Isolation system:

- One layer of Tedlar; or type 120 glass fabric with a compatible resin; or finish.

5.4.2 Composite Joints. Conduction between two composite members may be provided by a screen joint, an adhesive bond using a conductive metal-filled epoxy, or by metal fasteners such as rivets or bolts (Reference 149). Six joint configurations are shown in Figures 85 through 90 and assessed in Table 29. Metal connectors (Figure 89) are recommended for large space structures. Although the initial cost is high, the ease of fabrication in space may make this system the most cost effective. The second best method is a screen technique, shown in Figure 86. The metal splice (Figure 90), mechanical fastener (Figure 88), and metal-filled epoxy (Figure 87) need much improvement or research and development before they can be considered as applicable for assembly in space.

5.4.3 Static Drain. To support the use of graphite-epoxy composite structures in space, joints must be developed to provide electrical conduction between composite structural members for static drain and for a fault current return path. The static drain path is necessary because the effect of vehicle charging can be detrimental where the conducting sections of the vehicle are not bonded together. For example, consider a vehicle that is charged triboelectrically on the forward surfaces and discharged through corona or the plasma from the skirt at the edges. If the forward section is not electrically connected to the aft section, charge acquired on the forward section cannot flow to the aft section unless the potential difference between the sections becomes large enough for a spark discharge to occur. These spark discharges can be quite energetic because the capacitance between the sections may be several thousand picofarads and the sparkover voltage may be several kilovolts. Furthermore, the spark discharge will seek the easiest electrical path between the sections. If there is some electrical wiring routed across this gap, it is possible that the spark will travel through a shorter gap from the section to the wiring, through the wiring, and then through another short spark gap to the aft section. This, of course, would put a tremendous noise pulse on any data line. Also, it is possible that these spark discharges could fire electro-explosive devices.

5.5 Thermal Control. Thermal control can be done by either conduction to a cold plate or by circulating cooled gas (air) or liquids. To accomplish good

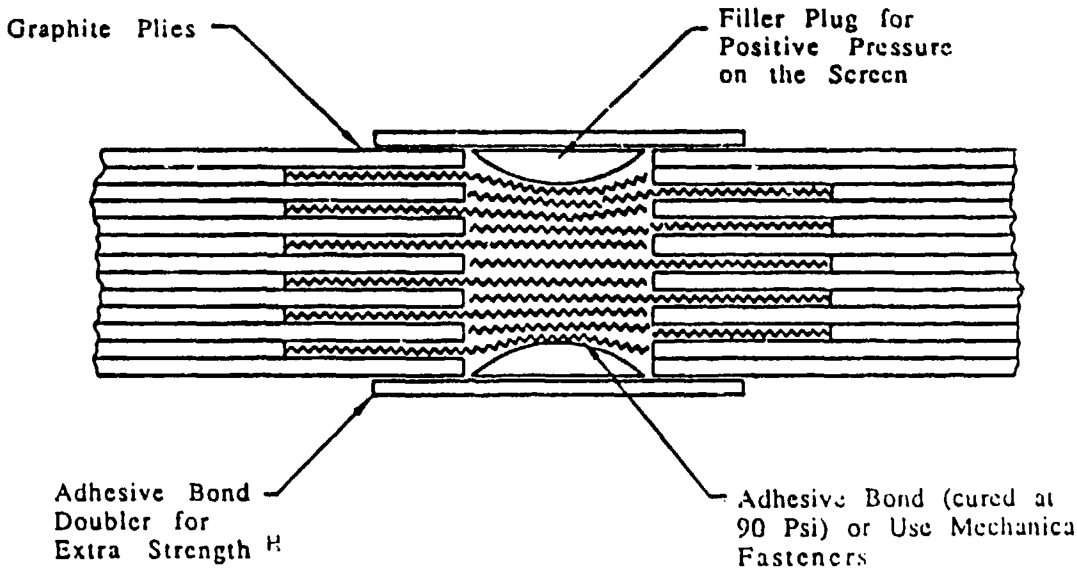

Figure 85. Multiple Screen Interleaved Lap Joint

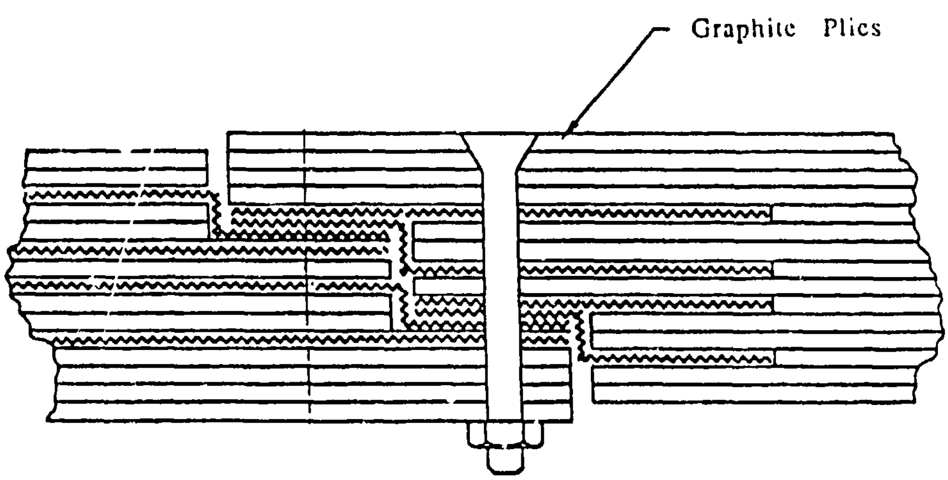

Figure 86. Multiple Exposed Screen, Mechanically Fastened Stepped Lap Joint

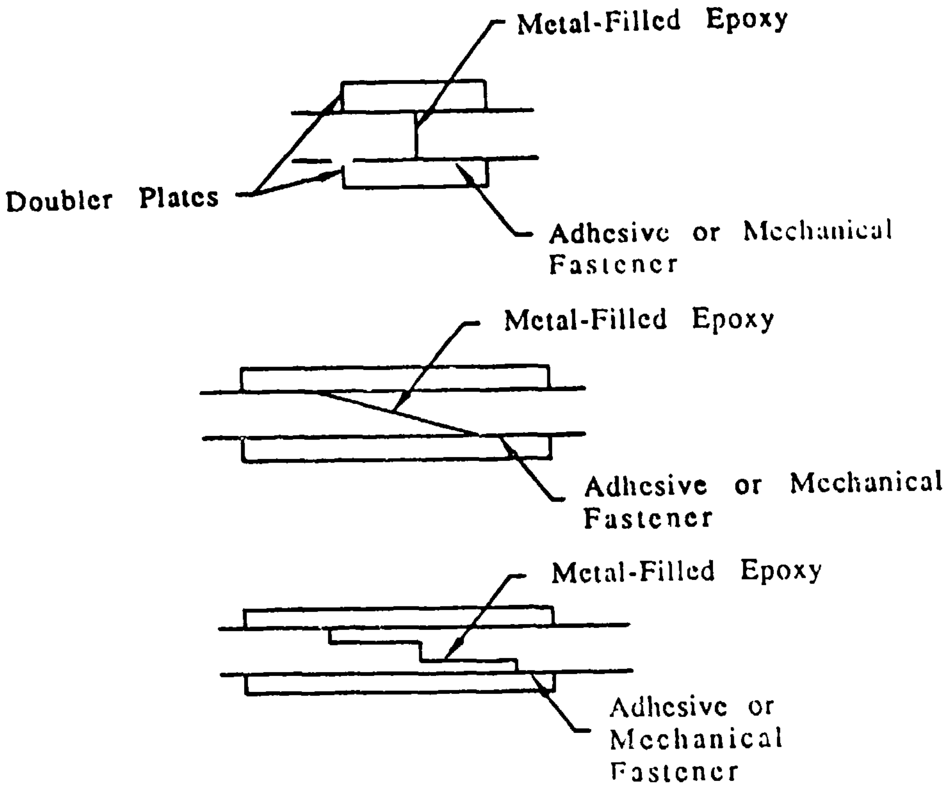

Figure 87. Butt,Scarf, and Stepped-Lap Joints

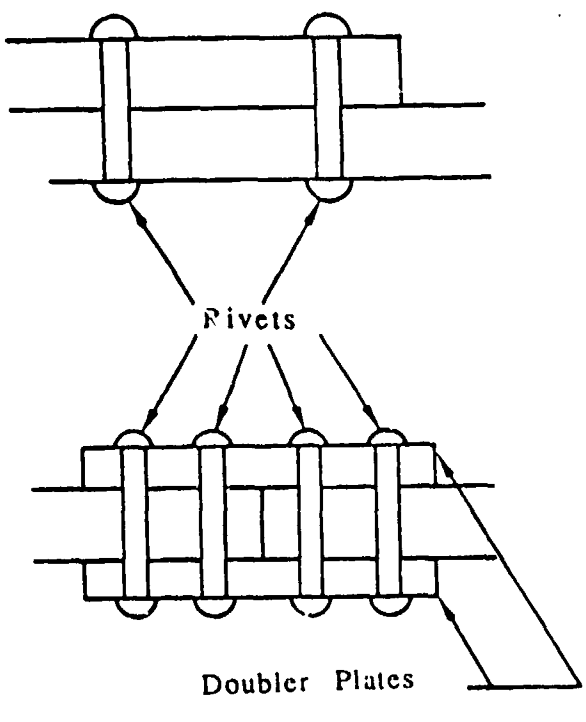

Figure 88. Mechanically Fastened Joints

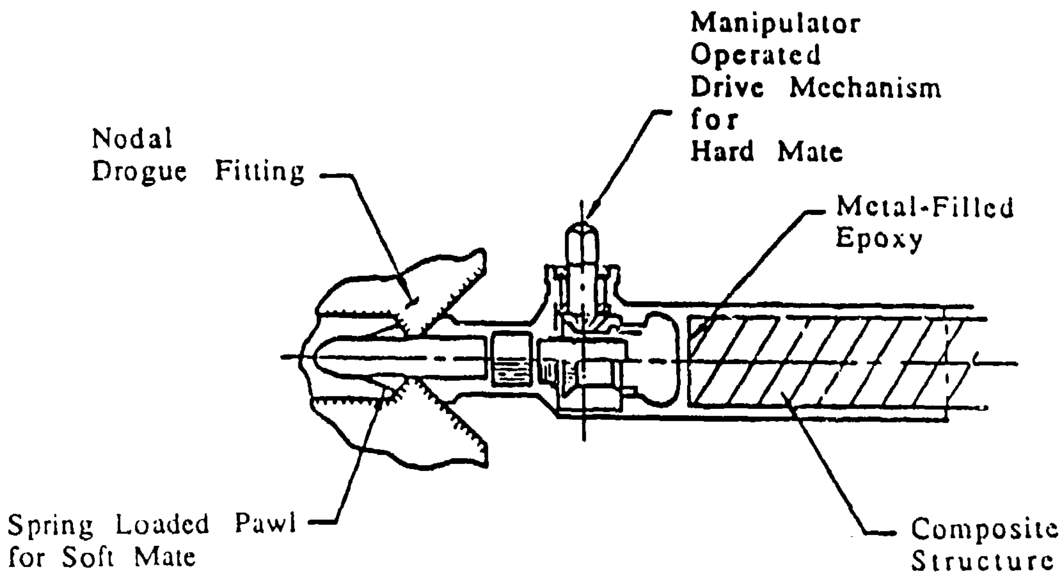

Figure 89. Metal Connector

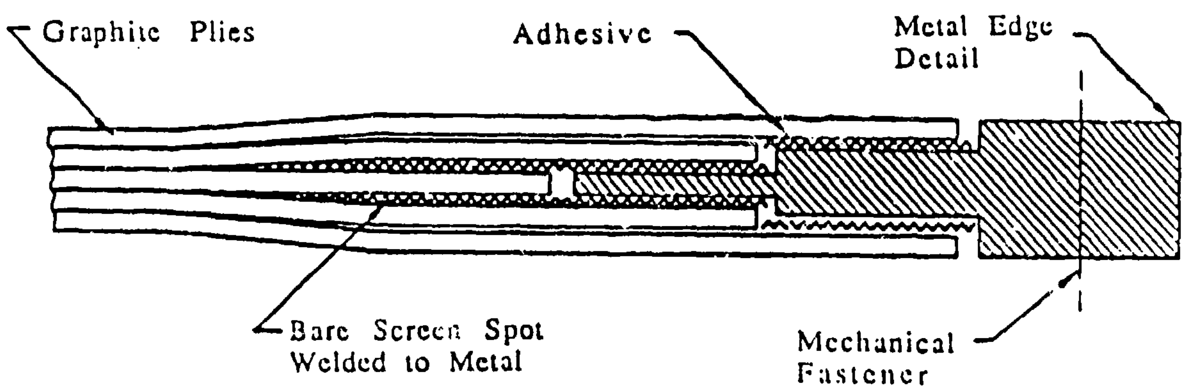

Figure 90. Center Screen Stepped Lap Composite to Metal Joint

TABLE 29

BONDING/GROUNDING CONCEPT ASSESSMENT

Joint	Advantages	Disadvantages
Screen (Fig. 85)	* Good electrical conductor	* Difficult to fabricate in space * Requires individual component layup * Requires doublers for mechanical strength
Screen (Fig. 86)	* Good electrical conduction * Inherent mechanical strength * Can be fabricated in space with pre-launch preparation	* Requires individual component layup
Metal-filled Epoxy (Fig. 87)	* Good electrical conduction * Can be used on cut ends of continuously formed members	* Difficult to fabricate in space * Requires doublers for mechanical strength
Mechanical Fasteners (Fig. 88)	* Inherent mechanical strength * Can be fabricated in space * Components may be joined at positions other than ends * Allows use of continuously formed members	* Poor electrical conduction
Metal Connectors (Fig. 89)	* Good electrical conduction * Inherent mechanical strength for truss structures * Easily fabricated in space with pre-launch preparation * Can be used on cut ends of continuously formed members	* Requires expensive and heavy connectors * Limited to truss structures
Metal Splice (Fig. 90)	* Good electrical conduction * Inherent mechanical strength for joining panels	* Cannot be fabricated in space * Required individual component layup

thermal control, all major dissipating components must be mounted to independent heat sinks providing the shortest heat path with as much surface area possible to the heat sink or cold plate. All semiconductors should have maximum junction temperatures less than 100°C for long life. Magnetic and some resistor elements may be allowed to have momentary hot spot temperatures to 125°C, but the average temperature should be kept to 85° to 100°C to preserve insulation life. To keep temperature under control encapsulant fillers, thermal conductive insulating boards, and thermally conductive compounds may be used to interface individual devices and parts with the heat sink to maintain the temperature goals.

Some power supply thermal design guidelines that should be followed are:

- Optimize component placement with respect to the coldplate
- Optimize component conductive surface area
- Minimize the thermal path
- Minimize the number of adjacent components conducting heat to a coldplate interface junction
- Use effective thermally conductive interface materials when possible
- Ensure safe operating temperatures for parts, devices, and materials

To ensure that the proper and accurate baseplate function, component, and device temperatures are calculated for each questionable component, it is important to develop and use a combination of (1) test data; (2) hand calculations for components, device, and part temperatures should be experimentally derived by test and analysis; and (3) an industry standard computer code with proven software. Simultaneous equations and matrix methods will be required for most densely packaged power supplies to obtain ± 5°C accuracy with respect to test data. The thermal analyses and electric field analyses should be developed simultaneously to optimize best field and thermal control. As in electric field analyses for solid-state chips encapsulated by the supplier, the maximum field stress may be inside the encapsulant. Thermal analyses must treat each part and component in the same manner,

the highest temperature will be, most probably, at the center or near the center of the part or component.

5.6 Structures. A mechanical engineer should develop designs and analyses to ensure all chassis internal components are capable of withstanding vibration and shock specifications. Models should be derived with components and structural members, potted within the designated chassis. These models should be given full military-specified environmental tests of temperature, vibration, and shock.

Debonding of encapsulants will generate partial discharge sites, which will result in insulation failure. After the first power supply unit has completed all environmental testing, the unit should be thoroughly inspected and tested for insulation delamination/debonding, cracking, and out-of-tolerance measurements.

The chassis should be designed with smooth rounded surfaces in the high voltage compartments. Chassis feedthrough parts should either be large to reduce electric field overstress, or corona shields should be placed inside the parts with smooth rounded surfaces facing the through wiring or part. Anodized or chemical conversion finish of 5 μinch finish is adequate, if the encapsulant bonds to the surface.

The best structural materials to form a high voltage standpoint are steel and nickel. Some metals have lower breakdown voltage when uncoated, and must be protected by coatings or encapsulation. Materials subject to lower breakdown include solder, silver, pure aluminum, and copper.

5.6.1 Wiring Layout. Many power supplies are very difficult to maintain and repair due to the "scramble" wiring technique used by manufacturing. Some power supplies appear as though all wires were cut to the same length and the remainder of each "stuffed" between components. Wires and wiring should be organized. If possible, three distinct layers should exist in the package. The lowest level next to the baseplate should be for grounds and voltages less than 50 volts, peaks. An effort should be made to separate the high voltage leads

from the lower voltage leads to reduce the opportunity for corona and partial discharges. Remember that all stranded wires have gas field conductors for the majority of the length of the wire.

Voltage levels may be bundled or grouped. Ties should not be placed on high voltage bundles or wires unless the tie ends are bonded to the conductors being tied. Likewise, ties, clamps, and sharp edges in low voltage or medium voltage wires should not face high voltage wires. Standoffs used to support high voltage and medium voltage wires should be electrically compatible.

5.6.2 Fiberglass Epoxy Boards. A fiberglass epoxy board should not be placed or bonded to a metal structure unless it is totally bonded to eliminate voids. If such a board is required, it would be better to use a metal-backed board, with the metal next to the chassis. Metals compatibility must be evaluated to prevent corrosion or electrolysis when potted. Using tin plated copper-backed boards is one way to reduce the probability of corrosion.

5.6.3 Field Modeling. It is a good practice to test the power supply for continuity and electrical continuity before incapsulation. This can be done by immersing the unit in a fluorocarbon fluid. A few things should be watched for, as suggested below:

- Fluorocarbon fluid is an excellent heat conductor and will not give a desirable thermal profile.
- Some fluorocarbons will take on water and other impurities, reducing their dielectric strength to unacceptable levels. This is especially true for voltages above 10,000 volts.
- The fluorocarbon must be completely dehydrated from the parts, modules, and wiring. This will take a long bake period. If not removed, the fluorocarbon could affect the dielectric properties of materials where it exists.
- Fluorocarbon is a cleaning fluid. Any inks or unstable unbonded material, dirt, and debris will be become loose and float about and between some high voltage parts and ground, causing unwanted problems.

SECTION VI
MATERIALS AND PROCESSES

The objective of this chapter is to give an electronic design engineer adequate materials and process information so he can communicate effectively with a materials and processes engineer. The materials and processes engineer should always be consulted when determining the chemical, mechanical, and thermal characteristics of materials. Processing is usually left to the materials and processing engineer, and the electrical testing and evaluation of the finished product is performed by the electronics engineer, except on receiving advice on how to make better use of materials and processes.

6.1 Insulation. There are hundreds of insulations available for high voltage power supplies, each claiming to solve all insulating and encapsulating problems. However, very few can meet the rigorous requirements for aerospace applications.

Insulation and insulation systems fall into two types of power supply design categories: (1) unpressurized or open construction and (2) pressurized or potted construction. Unpressurized constructed modules have outgassing ports that allow all parts and submodules within to eventually assume the pressure of the outside environment. Pressurized modules are gas- or liquid-filled modules. Liquid- and gas-filled modules may use solid insulating materials if they meet the electrical, chemical, and mechanical characteristic requirements imposed by the design and are compatible with the insulating gas or fluid.

6.1.1 Open Construction. Open construction design refers to modules with few or no solidly potted submodules. In this type of construction circuit boards must be conformally coated to reduce breakage due to vibration and shock, inhibit corrosion and fungus during handling and storage, and reduce surface tracking along board surfaces between high and low voltage parts, terminations or connections.

Before a board is conformally coated, it should be inspected. Flat surfaces mounted parallel to the board surface should be stacked 0.5 to 1.0 mm above the circuit board to allow the insulating material to flow into the interspace and fill the void between the part and the board. Then the following rules should apply:

a. All boards, conductors, wiring, and electrical components must be cleaned per the appropriate specification before the unit is conformally coated. This includes solder flux, fingerprints, particles from the workbench, and dust.

b. The circuit boards should be conformally coated with at least three separate layers of a low viscosity insulation. Application may be either by dipping or brushing, with each layer applied at right angles to the preceding layer. Three layers are recommended to eliminate the pinholes (continuous leakage path) and uncoated areas that normally occur in single or double coating processes. The completed process should be checked by an insulation test.

c. The final step in an electrical assembly is the joining of the printed circuit board assembly. If wired, the wire and solder joints must be cleaned and conformally coated with the same precaution as the electrical networks on the printed circuit boards after the connections are made to the other board subassemblies within the module.

In many cases a conformally coated board is then potted to take advantage of the strong points of both methods. When doing this, the board and assembled parts must be cleaned and care must be taken to ensure good bonding between the two substances.

Some materials used for conformal coatings include:

- Conathane CE 1155
- Uralane 5750
- Hysol PC 18M
- Solathane 113

Parylene is an excellent coating material; its drawbacks are poor adhesion to some materials, repairability, and cost. It does penetrate small interspaces and provides a fairly consistent coating on all surfaces.

6.1.2 Potted Construction. One method of preventing a gas discharge voltage breakdown is to exclude gases from the high voltage areas. This can be accomplished by encapsulating the high voltage circuitry. Encapsulation provides the system with mechanical protection from external damage, gives structural support to the components against shock and vibration, and protects the high voltage system from gas discharge damage.

The decision to encapsulate should be made during the initial design concept phase and incorporated in the subsequent hardware design. A total system approach to the design is taken, yielding a power supply with minimum problems that can arise from encapsulation or potting. This permits the optimum choice of components, parts, materials, mechanical arrangements, manufacturing techniques, and the methods of function and environmental testing. This approach reduces the failure probability. In a survey of U.S. Air Force, NASA, and industry, it was found that encapsulated electronics failures fall into four categories: high electric stress (packaging), selection of parts or improper use of parts (design), poor bonds, board delamination (material), voids, cracks, workmanship, and handling (processes). The evaluation of these items is summarized in Table 30 (Reference 150).

TABLE 30

SUMMARY OF FAILURE ANALYSES FROM SURVEY

ITEM	PERCENTAGE
Materials	15
Packaging	24
Design	25
Processes	36

Selecting the encapsulating material and designing and packaging the circuit can be accomplished with reasonable success; processing the materials gives the most trouble.

6.1.3 Encapsulant Selection. Three general classes of encapsulating, (potting) materials, or conformal coating materials are generally acceptable for aerospace use: epoxies, silicones, and polyurethanes. Table 31 shows properties of interest that must be considered in the encapsulant selection. Of these properties, some are more important than others. They are: (1) sufficiently low viscosity and sufficiently long pot life to give the highest potential for high yield, void-free encapsulation, thereby ensuring freedom from corona problems; (2) good thermal stability in terms of service temperature, weight loss, service life, etc., to minimize polymer degradation and outgassing in system use; (3) low thermal expansion to minimize system performance failures due to differential thermal expansion between normally low thermal expansion component parts and normally high thermal expansion encapsulating materials; (4) high track resistance to minimize potential of carbon path formation in arcing conditions that usually leads to early catastrophic system failure; and (5) good overall electrical characteristics, such as high dielectric strength, high resistivity, and low dielectric constant and dissipation factor. The best combination of these desirable characteristics is likely to give highest yield, highest reliability, encapsulated high voltage electronic modules. Some material properties that can be considered are listed Table 32, but few of them meet the requirements

TABLE 31

PROPERTIES OF INTEREST FOR INSULATING MATERIALS

MECHANICAL PROPERTIES	ELECTRICAL PROPERTIES	THERMAL PROPERTIES	CHEMICAL PROPERTIES	MISCELLANEOUS PROPERTIES
Tensile, compressive, shearing, and bending strengths	Electric strength	Thermal conductivity	Resistance to reagents	Specific gravity
Elastic moduli	Surface breakdown strength	Thermal expansion	Effect upon adjacent materials	Refractive index
Hardness	Liability to track	Primary creep	Electro-chemical stability	Transparency
Impact and tearing strengths	Volume and surface resistivities	Plastic flow	Stability against aging and oxidation	Color
Viscosity	Permittivity	Thermal decomposition,	Solubility	Porosity
Extensibility	Loss tangent	Spark, arc, and flame resistances	Solvent crazing	Permeability to gases and vapors
Flexibility	Insulation resistance	Temperature coefficients of other properties		Moisture Adsorption
Machinability	Frequency coefficients of other properties	Melting point		Surface adsorption of water
Fatigue		Pour point		Resistance to fungus
Resistance to abrasion		Vapor pressure		Resistance to aging by light
Stress crazing				

TABLE 32

DESIRED MATERIAL PROPERTIES

Electrical		Mecnanical	
Property	**Value**	**Property**	**Value**
Arc Resistance	> 60 sec	Shrinkage	
Dielectric Constant	>6	Volume	< 3%
Dielectric Strength	> 350 V/mil	Linear	< 3%
Dissipation Factor	< 0.02	Age	< 0.5%
Thermal Expansion	$< 300v10^{-6}$ cm/cm/^oC	Service Temp	$-55^o + 105^oC$
Thermal Conductivity	$>15x10^{-4}$Cal/sec/cm^2/^oC/cm		
Surface Resistivity	$> 10^{12}$ Ohms	Heat Distortion (Temperature)	$> 100^oC$
Volume Resistivity	$> 10^{12}$ Ohm-cm		
Moisture Absorption	< 1%	Coef. of Thermal expansion	$<1.5x10^4/^oC$
Fungus	Non Nutrient		

stated in the table. As an example, 68 materials properties are shown in Table 33.

None of these materials have ideal properties; therefore, the materials engineer and electronic designer must agree on the characteristics that are the most important and that can be tolerated.

6.1.4 Materials Evaluation. Data sheets showing the electrical, chemical, and mechanical properties for each material are usually limited to ASTM requirements. They do not include variance in mixing, shelf life (storage), and processing. For example, addition of filler changes some of the properties considerably.

6.1.4.1 Concentric-Cylinder Test Fixture. The concentric-cylinder test is a nonstandard ASTM test that may be inappropriate for many potting applications. The test was designed to evaluate and simulate thermal-mechanical stresses within high voltage potting compounds confined between rigid surfaces, such as traveling wave tubes; transformer windings, cores, and bobbins; and parallel metallic or ceramic surfaces (Reference 151). When a material fails to pass this rigorous test, it does not imply that the material is unacceptable as a high voltage potting material. It only suggests that a few material applications are too restrictive for all materials.

The test cell is constructed from two concentric aluminum tubes. The outer tube has a 1.75-inch inside diameter and the centered inner tube has a 1-inch outside diameter. These tubes are set up vertically on a flat surface and filled with potting compound. Figure 91 is a photograph of the test cell parts and the assembled test cell. The test cell determines the adhesion properties with concave and convex surfaces and whether the shrinkage of the material on curing and testing will break the adhesion. A potting material that wets well, a desirable characteristic, will have a concave meniscus at the top surface. It was found necessary to provide a similar configuration at the bottom surface, as shown in Figure 91, to avoid a stress concentration at this point during thermal shock testing. The necessity for stress relief by avoiding

TABLE 33

MATERIALS PROPERTIES - ELECTRICAL

			ARC RESISTANCE	DIELECTRIC CONSTANT	DISSIPATION FACTOR	DIELECTRIC STRENGTH V/MIL	RESISTIVITY SURFACE OHM	RESISTIVITY VOLUME OHM - CM	TRANSPARENCY COLOR	MOISTURE ABSORPTION	REVERSION RESISTANCE	WATER PERMEABILITY $\frac{g}{hr\text{-}cm}$	FUNGUS RESISTANCE	SPECIFIC GRAVITY
TARGET PROPERTIES				< 6.0			> 10^{12}	> 10^{12}			YES		Non-Nutrient	
FLEXIBLE MATERIALS														
SILICONES														
UNFILLED														
SYLGARD	182	DC							Cl	.1%				1.05
SYLGARD	184	DC							Cl	.1%				1.05
SYLGARD	186	DC		3.0 100 KHz	.001 100 KHz	575	7×10^{16}	2.4×10^{13}	Cl	.15%	YES	1.0×10^{-7}	NON NUTR	1.12
RTV	602	GE		3.0 100 KHz	.0012 100 KHz	500		1×10^{14}	Cl	.08%	YES		NON NUTR	1.004
RTV	615	GE		3.0 1 KHz	.01 1 KHz	500		4.5×10^{13}	Cl	.05%	YES		NON NUTR	1.02
RTV	619	GE		3.0 1 KHz	.001 1 KHz	500		1×10^{15}	Cl					.97
FILLED														
SILASTIC	E (93-072)	DC							OP-WH					1.12
SILASTIC	881	DC		2.9 1 MHz		550		1×10^{14}	OP	.4%				1.13
CHEM SEAL	3808	CS	50 sec	5.0 1 MHz		300		1×10^{13}	OP-RED		NO			1.47
DC	3116	DC	90 sec	5.5 10 KHz	.03 10 KHz	500		1×10^{13}	OP-WHITE	.4%				1.17
SYLGARD	170	DC		3.1 100 KHz	.002 100 KHz	450		1×10^{15}	OP BLK	.1%				1.38
SYLGARD	96-082	DC		2.99 100 KHz	.002 100 KHz	500	5×10^{15}	5×10^{14}	OP BLK					1.21
GELS														
DC	51	DC		3.0 100 KHz	.0001 100 KHz	500		1×10^{11}	Cl					.97
DC	F-1-3521	DC		2.7 100 KHz	.0001 100 KHz	450		1×10^{14}	Cl					.97
URETHANES														
FILLED														
CONATHANE	EN-2523	CON	130 sec	3.5 1MHz	.012 1MHz	630	2.6×10^{12}	3.4×10^{13}	OP TAN	.14			NON NUTR	1.44

MATERIALS PROPERTIES

LITERATURE

TABLE 33

MATERIALS PROPERTIES - ELECTRICAL (Con't.)

			ARC RESISTANCE	DIELECTRIC CONSTANT	DISSIPATION FACTOR	DIELECTRIC STRENGTH V/MIL	RESISTIVITY SURFACE OHM $>10^{12}$	RESISTIVITY VOLUME OHM-CM $>10^{12}$	TRANSPARENCY COLOR	MOISTURE ABSORPTION	WATER PERMEABILITY $\frac{g}{hr\text{-}cm}$	REVERSION RESISTANCE YES	FUNGUS RESISTANCE NON NUTRIENT	SPECIFIC GRAVITY
SEMI-FLEXIBLE MATERIALS				≤ 6.0										
	TARGET PROPERTIES													
URETHANES														
UNFILLED														
PR	1527-M	PRC	194 sec	4.1 1 MHz	.09 1 MHz	310		$2.5x10^{11}$	OP Amb - Blk			YES	non nutr	1.06
PR	1546	PRC		4.5 1 MHz	.05 1 MHz	330		$1.51x10^{13}$	Cl Straw			NO		1.04
PR	1578	PRC							Cl Amber					1.07
PR	1592	PRC	150 sec	4.6 1 MHz	.06 1 MHz	300	$1x10^{13}$	$1x10^{12}$	Cl Dk Amber	2.4%		YES	non nutr	1.08
SCOTCHCAST	221	3M		3.0 100 KHz	.05 100 KHz	340		$1.3x10^{13}$	CL Amb	.23%		NO		1.06
CONATHANE	EN-2522	CON	160 sec	3.3 1 MHz	.016 1 MHz	610	$1.0x10^{13}$	$1.2x10^{14}$	CL DK AMBER	.22%			non nutr	1.1
SOLITHANE	113	THI		2.55 1 MHz	.012 1 MHz	400	$1.5x10^{15}$	$3.0x10^{13}$	CL Amb	.23%		NO		1.04
FILLED														
CONATHANE	EN-2521	CON	130 sec	3.7 1 MHz	.016 1 MHz	650	$2.0x10^{13}$	$1.2x10^{14}$	OP - Tan	.19%			non nutr	1.53
SOLITHANE/ CABOSIL	113	THI												
ISOCHEMREZ	468	ISO		4.61 100 KHz	.025 100 KHz	450		$1x10^{13}$	Cl	.10%				1.15
POLYSULFIDES														
FILLED														
PROSEAL	727	PRC	25 sec	9.5 1 MHz	.03 1 MHz		$1x10^{12}$	$1x10^{11}$	OP - Lt Brn				non nutr	
PR	1201 Q	PRC	50 sec	9.3 1 MHz	.024 1 MHz	220	$1.2x10^{12}$	$1.9x10^{11}$	OP - Red-Brn					
GC	1300	GRO	81 sec	9.9 1 MHz	.014 1 MHz	267	$1.2x10^{12}$	$8.7x10^{11}$	OP - Brn					
POLYBUTADIENES														
FILLED														
CB	1109	DOL		2.91 - 1 MHz	.020 1 MHz	665	$3.[illegible]x10^{14}$	$1.78x10^{15}$	OP - Blk					1.2
Poly bd	2-011	ARCO		2.94 - 1 MHz	.021 - 1 MHz		$3.06x10^{14}$	$1.75x10^{15}$						
PHENOLIC - OIL														
FILLED														
C	1525A	VIK				1260			Cl - Lt Brn	.16%				
C	1525F-35	VIK				1000			OP - Blk	.16%				
C	1525G-45	VIK				[illegible]			OP - Tan	.16%				

MATERIALS PROPERTIES
LITERATURE

TABLE 33

MATERIALS PROPERTIES - ELECTRICAL (Con't.)

			ARC RESISTANCE	DIELECTRIC CONSTANT	DISSIPATION FACTOR	DIELECTRIC STRENGTH V/mil	SURFACE OHMS	VOLUME OHM-CM	TRANSPARENCY COLOR	MOISTURE ABSORPTION	WATER PERMEABILITY $\frac{g}{hr\text{-}cm}$	REVERSION RESISTANCE	FUNGUS RESISTANCE NON-NUTRIENT	SPECIFIC GRAVITY
RIGID MATERIALS														
TARGET PROPERTIES				≤ 6.0			$>10^{12}$	$>10^{12}$				YES		
EPOXIES														
UNFILLED														
SCOTCHCAST	5	3M		3.9 100 Hz	.08 100 Hz	325		$1x10^{14}$	Cl	.2%				
SCOTCHCAST	8	3M		5.0 100 Hz	.098 100 Hz	350		$3.8x10^{14}$	Cl	1.?%				1.15
ISOCHEMREZ	460	ISO		4.1? 100 KHz	.018 100 Hz	420		$1x10^{14}$	Cl	.11%				
SCOTCHCAST	280	3M		?66 100 Hz	.012 100 Hz	375				.52%			non nutr	1.15
STYCAST	1264	EC		3.5 1 MHz	.028 1MHz	42?	$9.1x10^{14}$	$5.1x10^{13}$	Cl - Blue	.37%				1.05
ISOCHEMREZ	402-LV	ISO		4.0 100 KHz	.035 100 KHz	410		$1x10^{13}$	OP - Blk	.11%				1.18
CONAPOXY	TH-1145	CON		3.7 119 Hz	.004 1 MHz			$7.1x10^{12}$	Cl - Aml					1.14
NORDBAK	1-0012	REX	45 sec	3.6 1 KHz	.034 1 KHz	390		$3.9x10^{14}$	Cl - Amb					1.07
NORDBAK	1-0021	REX	30 sec	3.6 1 KHz	.041 1KHz			$4.4x10^{15}$	Cl - Amb					
FILLED														
SCOTCHCAST	281	3M		3.56 100 Hz	.054 100 Hz	375		$1x10^{15}$	OP - Brn	.32%				
PR	2200	FRI		4.2 60 Hz	.018 60 Hz	480		$1.5x10^{16}$	OP - Blk					1.45
PDR	1322	DOL				450	$> 1x10^{6}$							1.37
ISOCHEMREZ	492AP	ISO		4.2 100 KHz	.005 100 KHz	410		$1x10^{4}$	OP - Blk	.09%				1.38
ISOCHEMREZ	405M50	ISO		4.4 100 KHz	.010 100 KHz	455		$1x10^{16}$	OP - Blk	.09%				1.55
SCOTCHCAST	9	3M		5.34 100 Hz	.061 100 Hz	350		$4.8x10^{14}$	OP - Brn	.67%				
STYCAST	1090	EC		3.1 1 MHz	.01 1 MHz	.375		$3.6x10^{13}$	OP - Blk	.23%				.81
STYCAST	1090SI	EC		2.9 1 MHz	.01 1 MHz	375		$1x10^{13}$	OP - Blk	.52%				.79
STYCAST	2651 MMFR	EC		4.2 10 GHz	.02 10 GHz	440		$5.6x10^{13}$	OP - Blk	.06%	$1.2x10^{-5}$			1.62
STYCAST	2850 FT	EC		5.9 1 MHz	.02 1 MHz	380		$4.3x10^{10}$	OP - Blk	.08%			non nutr	2.3
HYSOL	C-6B	HY		4.24 10 KHz	.006 10 KHz	750		$2.1x10^{11}$	OP - Gry	.002%				
SCOTCHCAST	XR-5068	3M (Syntactic Foam)		2.0 1 MHz	.08 1 MHz			$1x10^{12}$	OP - LT Orange					.21
SCOTCHCAST	247	3M	68 sec	4.3 1 KHz	.03 1 KHz	400	$1x10^{12}$	$4x10^{13}$	OP - Brn	.11%	$2.0x10^{-5}$			1.55
RIPLEY RESIN	484-XD-10	RIP		4.03 1 KHz	.048 1 KHz	610			OP - Blue					
RIPLEY RESIN	494-XD-??	RIP		4.03 1 KHz	.048 1 KHz	610			OP - Tan					
RIPLEY RESIN	2468-MA-3	RIP		2.4 1 MHz	.008 1MHz	580				.035%				
NORDBAK	1-005?	REX	122 sec	3.9 1 KHz	.006 1 KHz			$4.7x10^{15}$	OP - Blk					1.5
NORDBAK	1-0061	REX	70 sec	4.1 1 KHz	.0049 1 KHz			$6.8x10^{14}$	OP - Blk					1.29
HYSOL	ES0264	HY	144 sec	4.2 100 KHz	.034 100 KHz		$8x10^{13}$	$1x10^{14}$		.22%				
HYSOL	977-87	HY	123 sec	3.51 100 KHz	.0086 100 KHz	567		$1.06x10^{16}$	OP - Tan					
POLYESTER														
UNFILLED														
STYPOL	40-1021	FRE								.22%				
STYPOL	40-1124	FRE	92 sec	3.03 1 MHz	.014 1 MHz	540 V/mil Step				.32%				1.068
STYPOL	40-1037	FRE												
FILLED														
STYPOL	40-1602	FRE							OP - Blk	.27%				1.54

TABLE 33

MATERIALS PROPERTIES - MECHANICAL (Con't)

FLEXIBLE MATERIALS	TARGET PROPERTIES		THERMAL SHOCK RESISTANCE	SHRINKAGE V=VOLUME L=LINEAR	AGE SHRINKAGE	HARDNESS A-D = SHORE	IMPACT RESISTANCE	ELONGATION	SERVICE TEMPERATURE	HEAT DISTORTION TEMPERATURE	COEFFICIENT THERMAL EXPANSION	THERMAL CONDUCTIVITY
SILICONES									-55°C-+105°C			
UNFILLED												
SYLGARD	16[illegible]	DC	Pass 10- MIL-1-16923									
SYLGARD	184	DC	Pass 10 MIL-1-16923			40A		100%	-65°C+200°C			
SYLGARD	186	DC		0%V		35A		100%	-65°C+200°C			3.5x10^-4 cal-cm
RTV	602	GE	5- -85°F +0 257°F	.60%V	.44%V	40A		480%	-65°F+480°F			3.5x10^-4 cal-cm 1.3 BTU-in
RTV	615	GE		1.21%V	1.11%V	15A			-90°F+300°F		1.6x10^-4/°F	1.07 BTU-in
RTV	619	GE			.98%V	25A		150%	-80°F+390°F		1.8x10^-4/°F 1.54x10^-4/°F	1.23 BT[illegible]-in
FILLED												
SILASTIC	E (93-072)	DC										
SILASTIC	881	DC		.7%L		30A		325%				
CHEM SEAL	3808	CS		5%V		35A						
DC	3116	DC	Pass 10- MIL-1-16923			50A			-67°F+482°F			
SYLGARD	170	DC	Pass MIL-1- 16923	.4%L		40A 55A		225% 150%	-65°C+250°C			
SYLGARD	96-082	DC				35A		150%	-65°C+250°C		8x10^-[illegible] °C	5.2x10^-5 cal-cm
GELS												
DC	51	DC										
DC	F-1-3523	DC							150°C -65°C		1% per 10°C 1% per 10°C	7x10^-4 cal-cm
URETHANES												
FILLED												
CONATHANE	CN-2523	CON	Pass 10- -65 to +190°C	.59% L		55-D		50%	-55°C-+130°C		15x10^-5/°C	4.5x10^-4 cal-cm

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MATERIALS PROPERTIES - MECHANICAL (Con't.)

SEMI-FLEXIBLE MATERIALS	TARGET PROPERTIES		THERMAL SHOCK RESISTANCE	SHRINKAGE V-VOLUME L=LINEAR	AGE SHRINKAGE	HARDNESS SHORE	IMPACT RESISTANCE	ELONGATION	SERVICE TEMPERATURE -55°C to +105°C	HEAT DISTORTION TEMPERATURE	COEFFICIENT THERMAL EXPANSION	THERMAL CONDUCTIVITY
URETHANES												
UNFILLED												
PR	1527-M	PRC		2.5%V		82 - A		563%	$-70^{o}F$ $+300^{o}F$		$1.0\times10^{-4}/^{o}F$	
PR	1546	PRC				50 - A		100%	$-65^{o}F$ $+300^{o}F$		$1.35\times10^{-4}/^{o}F$	1.025 BTU-in
PR	1578	PRC				80 - A		600%	$-320^{o}F$			
PR	1592	PRC				85 - A		425%				
SCOTCHCAST	221	3M	$10\sim -65^{o}F$ $+265^{o}F$	1.7%V	.18%V	60 - A	23.4 ft-in MIL-I-16923	65%	$266^{o}F$		$1.17\times10^{-4}/^{o}F$	1.22 BTU-in
CONATHANE	EN-2522	CON	10 $-65^{o}C$ $+130^{o}C$	.91%L		55 - D		80%	$-55^{o}C$-$+190^{o}C$		$21\times10^{-5}/^{o}C$	2.6×10^{-4}Cal-cm
SOLITHANE	113	THI		4.%V		60 - A	107 ft-in	100%			$5.4\times10^{-5}/^{o}F$	
FILLED												
CONATHANE	EN-2521	CON	PASS $10\sim$ -65 + $130^{o}C$	.71%L		72 - D		40%	-55-$+130^{o}C$		$16.10^{-5}/^{o}C$	6.5×10^{-4}Cal-cm
SOLITHANE/CABOSIL	113	THI				60 - A			$-40^{o}F$-$+200^{o}F$			
ISOCHEMREZ	468	ISO		.40%L		74 - D			$-60^{o}C$ $+200^{o}C$		$7.1\times10^{-5}/^{o}C$	6.3×10^{-4}Cal-cm
POLYSULFIDES												
FILLED												
PROSEAL	727	PRC		12%V		50 - A						
PR	1201	PRC		12%V		40 - A			$-70^{o}F$-$+225^{o}F$			
GC	1300	GRO				45 - A			$-70^{o}F$			
POLYBUTADIENES												
FILLED												
CB	1109	DOL	$-72^{o}C$ FLEX	.021%		45 - A		180%				
POLY bd	2-011	ARCO						285%				
PHENOLIC - OIL												
FILLED												
C-	1525A	VIK		.2%					$-85^{o}F$ + $400^{o}F$			
C	1525F-35	VIK		.15%		30 - A_2			$-85^{o}F$ + $400^{o}F$			
C	1525G-45	VIK		.15%					$-85^{o}F$ + $400^{o}F$			

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MATERIALS PROPERTIES - MECHANICAL (Con't.)

RIGID MATERIALS	TARGET PROPERTIES		THERMAL SHOCK RESISTANCE	SHRINKAGE V = VOLUME L - LINBAR	AGE SHRINKAGE	HARDNESS A-D = SHORE	IMPACT RESISTANCE	ELONGATION	SERVICE TEMPERATURE -55°C to +105°C	HEAT DISTORTION TEMPERATURE	COEFFICIENT OF THERMAL EXPANSION	THERMAL CONDUCTIVITY
EPOXIES												
UNFILLED												
SCOTCHCAST	5	3M	Fail			35 Barcol		1.4%			177×10^{-10}/ °C	4.4×10^{-4} Cal-cm
SCOTCHCAST	8	3M	Pass MIL-I-16923			70 D		50%			15×10^{-5}/°C	4.2×10^{-4} Cal-cm
ISOCHEMREZ	460	ISO		.85%L		88 D			-55°C + 250°C	192°C	6.2×10^{-5}/°C	4.8×10^{-4} Cal-cm
SCOTCHCAST	280	3M	Pass MIL-I-16923			65 D		85%			21×10^{-5}/°C	5.3×10^{-4} Cal-cm
STYCAST	1264	EC	10 -45°F+160%	5.0% V	.51%	84-D	50 in-lb		185°F		5.9×10^{-5}/°F	
ISOCHEMREZ	402-LV	ISO		.88%L		86-D			-35°C to+190°C	118°C	6.2×10^{-5}/°C	4.5×10^{-4} Cal-cm
CONAPOXY	IM-1145	CON		2.1% L		80-D		7%				
NORDBAK	1-3012	REX	Pass Washer -55°C +155°C			61-D						
NORDBAK	1-9921	REX	Pass Washer -55°C +155°C			40 D		75%				
FILLED												
SCOTCHCAST	281	3M	Pass MIL-I-16923			65 D		45%			15×10^{-5}/°C	12×10^{-4} Cal-cm
PR	2200	FRI		5 Mil/inch²		75-D			-55°C+170°C	95°C	2.7×10^{-5}/°C	3.4 BTU-in
PDR	1322	DOL				72-D						
ISOCHEMPEZ	402AP	ISO		.49%L		88-D			-35°C+150°C	132°C	5.3×10^{-5}/°C	7.8 BTU-in
ISOCHEMPEZ	405M50	ISO		.48L		88 D			-45°C+200°C	165°C	5.1×10^{-9}/°C	8.2 BTU-in
SCOTCHCAST	9	3M	Pass MIL-I-16923			70-D					13×10^{-5}/°C	7.4×10^{-4} Cal-cm
STYCAST	1090	EC		3.1% V	0%	76-D			-65°F+280°F		2.06×10^{-5}/°F	.86 BTU-in
STYCAST	10951	EC		2.8% V	0%	76-D			225°F		2.2×10^{-5}/°F	.7 BTU-in
STYCAST	2651 MMER	EC	Pass 10 MIL-I-16923	2.8% V	0%	92-D	.2 ft lb/in 1200		-65°F+350°F		1.9×10^{-5}/°F	1.02 BTU-in
STYCAST	2850 FT	EC		1.7% V	0%	84-D	.3 ft lb/in 1200		300°F		1×10^{-5}/°F	3.3 BTU-in
HYSOL	C-68	HY	Pass-55°C	.1% L		120 Rock-M	.45 ft-lb/in 120D			100°C	23.5×10^{-6}/°C	3.34 BTU-in
SCOTCHCAST	XR-5068	3M						0%	265°F		13×10^{-5}/°C	5.7×10^{-4} Cal-cm
SCOTCHCAST	247	3M	MIC-1-16923 TYP C	2.1% Vol	0%	57 Shore D	12 Ft-lb	54%	265°F			.37 BTU-in
RIPLEY RESIN	484-YD-10	RIP	Pass -55°to 150°C			87 D		9.2%				.37 BTU-in
RIPLEY RESIN	494-YD-10	RIP	Pass -55°to 150°C			88 D		9.2%			2.8×10^{-5}/°F	.57 BTU-in
RIPLEY RESIN	2468-MA-3	RIP	Pass -55°Cto150°C			87 D		6.3%				
NORDBAK	1-0059	REY	Washer -55°C-155°C			75 D						
NORDBAK	1-0061	REY	Washer -55°C-155°C			60 D					20×10^{-5}/°C	
HYSOL	ES0254	HY		8%				9%				7.31×10^{-4} Cal-cm
HYSOL	977-87			1.85%L				1.65%				
POLYESTER												
UNFILLED												
STYPOL	40-1021	FRE				40 A		250%				
STYPOL	40-1124	FRE		8.4%		70 A						
STYPOL	40-1037	FRE										
FILLED												
STYPOL	40-1602	FRE		7.2%		70 D			-55°C + 105°C			
STYPOL	40-1603	FRE		6.7%		60 D			-55°C + 105°C			
URETHANES												
UNFILLED												
CONATHANE	EN-2526	COM		.93 L		80 D		10%	-20°C+130°C		21×10^{-5}/°C	2.9×10^{-4} Cal-cm

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MATERIALS PROPERTIES - MECHANICAL (Con't.)

TARGET PROPERTIES			MODULUS TENSILE 500,000 psi	MODULUS FLEXURAL 450,000 psi	MODULUS COMPRESSIVE 425,000 psi	STRENGTH TENSILE psi	STRENGTH FLEXURAL psi	STRENGTH COMPRESSIVE psi	VISCOSITY CPS
FLEXIBLE MATERIALS									
SILICONES									
UNFILLED									
SYLGARD	182	DC				900			5,500
SYLGARD	184	DC				900			5,500
SYLGARD	186	DC				800			60,000
RTV	602	GE							1,500
V	615	GE				900			3,500
V	619	GE							500
FILLED									
SILASTIC	E (93-072)	DC				750			65,000
SILASTIC	881	DC				300			
CHEM SEAL	3808	CS				650			70,000
RTV	3116	DC				375			50,000
SYLGARD	170	DC				500			3,000
SYLGARD	95-082	DC				250			1,500
GELS									
DC	51	DC							600 CSTKS
DC	F-1-3523	DC							500 CSTKS
URETHANES									
FILLED									
CONATHANE	EN-2523	CON				1600			2,800

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MATERIALS PROPERTIES - MECHANICAL (Con't.)

				MODULUS		STRENGTH			
			TENSILE	FLEXURAL	COMPRESSIVE	TENSILE	FLEXURAL	COMPRESSIVE	VISCOSITY cps
SEMI-FLEXIBLE MATERIALS									
URETHANES	TARGET PROPERTIES		500,000 psi	450,000 psi	425,000 psi	psi	psi	psi	
UNFILLED									
PR	1527-M	PRC				2,360			19,500
PR	1546	PRC				1,000			15,000
PR	1578	PRC	500 (100%)			5,000			37,000
PR	1592	PRC	600 (100%)			6,000			20,000
SCOTCHCAST	221	319				225			900
CONATHANE	EN-2522	CON				2,[illegible]00			420
SOLITHANE	113	THI				400			4,000
FILLED									
CONATHANE	EN-2521	CON				1,600			4,000
SOLITHANE/CABOSIL	113	THI							
ISOCHEMREZ	468	ISO				5,220		6,645	800
POLYSULFIDES									
FILLED									
PROSEAL	727	PRC							50,000
PR	1201 Q	PRC							55,000
GC	1300	GRO							55,000
POLYBUTADIENES									
FILLED									
CB	1109	DOL				1,260			8,400
POLY bd	2-011	ARCO	365 (100%)			820			
PHENOLIC - OIL									
FILLED									
C-	1525A	VIK							3,500
C	1525F-35	VIK							12,000
C	1525G-45	VIK							12,000

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MATERIALS PROPERTIES - MECHANICAL (concluded)

RIGID MATERIALS			MODULUS TENSILE	MODULUS FLEXURAL	MODULUS COMPRESSIVE	STRENGTH TENSILE	STRENGTH FLEXURAL	STRENGTH COMPRESSIVE	VISCOSITY
EPOXIES	TARGET PROPERTIES		500,000 psi	450,000 psi	425,000 psi	700 psi	psi	psi	cps
UNFILLED									
SCOTCHCAST	5	3M				6200	19,000	21,800	3000
SCOTCHCAST	8	3M				2000	1,400	3,000	5500
ISOCHEMREZ	460	ISO				9200		16,000	26,000
SCOTCHCAST	280	3M				1950	425	2,400	4000
STYCAST	1264	EC							440
ISOCHEMREZ	402-LV	ISO				4800		6,800	550
CONAPOXY	TM-1145	CON				7000			1400
NORDBAK	1-0012	REX				2400		30,000	650
NORDBAK	1-0021	REX				500		510	1500
FILLED									
SCOTCHCAST	281	3M				2100	1,250	3,500	48,000
PR	2200	FRI				10,500		16,000	5,000
PDR	1322	DOI							2,500
ISOCHEMREZ	402AP	ISO				6200		8,500	2,800
ISOCHEMREZ	405M50	ISO				9000		16,000	17,500
SCOTCHCAST	9	3M				2500	2,600	4,500	
STYCAST	1090	EC			238,000		4,200	16,000	20,000
STYCAST	10951	EC			250,000		4,000	10,000	18,000
STYCAST	2651 MMER	EC				7000	12,000	17,000	4,500
STYCAST	2850 FT	EC		2×10^6	1.1×10^6	8400	13,300	16,500	70,000
HYSOL	C-68	HY					12,500	30,500	17,000
SCOTCHCAST	XR-5068	3M						110 psi	Powder
SCOTCHCAST	247	3M				1250	265	1,390	35,000
RIPLEY RESIN	484-YD-10	RIP				4400			28,500
RIPLEY RESIN	494-YD-10	RIP				4400			30,000
RIPLEY RESIN	2468-MA-3	RIP				4400			56,000
NORDBAK	1-0059	REY				3400		11,800	7,000
NORDBAK	1-0061	REY							2,000
HYSOL	ES0254	HY		3×10^5		4000	7,000		10,000
HYSOL	977-07			9.55×10^5		9636	13,644		
POLYESTER									
UNFILLED									
STYPOL	40-1021	FRE				400			280
STYPOL	40-1124	FRE							175
STYPOL	40-1037	FRE							250
FILLED									
STYPOL	40-1602	FRE				1800	620		35,000
STYPOL	40-1603	FRE							35,000
URETHANES									
UNFILLED									
CONATHANE	EN-2526	CON				5600			280

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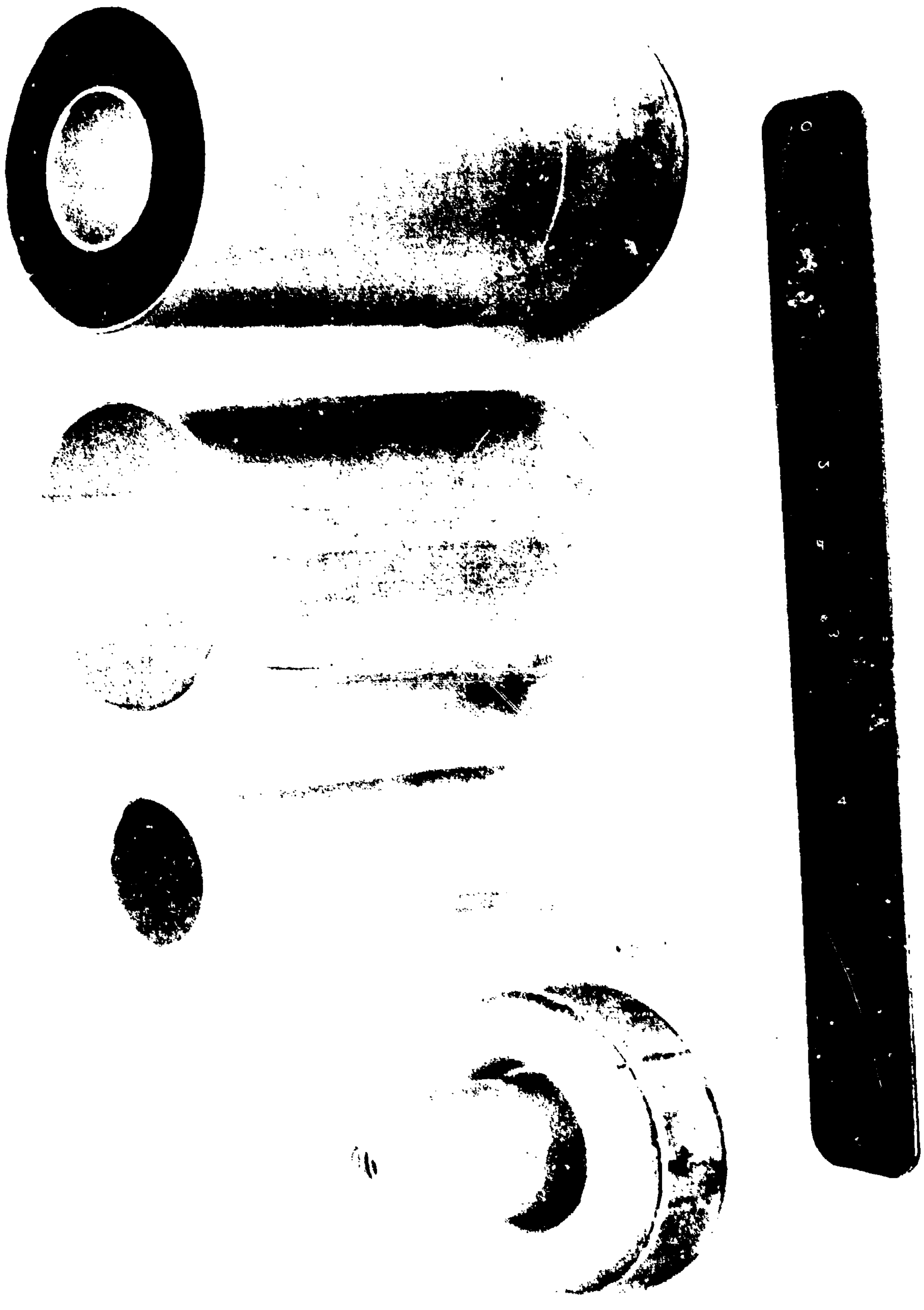

Figure 91. Concentric Cylinder Assembly

sharp inside corners should be applied to the design of the power supply enclosure.

6.1.4.2 Thermal Shock Adhesion Tests. Testing is done by placing the cured test material and test cell alternately in an oven and a cold box. A test condition of 2 hours at high temperature followed by 2 hours at low temperature, with less than 1 minute transfer time between temperature extremes is good for thermal shock evaluation. The material fails if it cracks or unbonds from the aluminum tubing at any location. Evaluation for cracks and voids is made by testing each test sample before and after each thermal-shock test. The cylinder and material must be cleaned and dried before partial discharge testing to remove residues accumulated by handling and humidity. Most acceptable materials will pass five to seven thermal shock cycles. Excellent materials will survive over 20 thermal shock cycles. After the thermal shock tests, the samples should be visually tested for cracking, bonding, and adhesion. If they pass the visual test they should be tested for breakdown voltage and partial discharges.

6.1.4.3 Mini-Wound Transformer Test. Materials that survive the concentric-cylinder and thermal shock tests should be evaluated in a mini-wound transformer test. This test is used to determine:

- The capability of the material to impregnate the windings and coil separating materials
- Adhesion to the winding insulation
- Separation of the filters from the resin during impregnation

Conformance to design detail is important in this test. The same conductor size and material, mats, tabs, sleeves, cores, and tapes should be used. The only difference is the overall physical size. Following construction and cleaning, the transformers should be potted and cured for at least 3 days before test. Tests should include visual, dielectric withstanding voltage, and partial discharge tests following at least 20 thermal cycles.

6.1.4.4 Materials Characterization. A chemical characterization analysis should be performed on the selected materials to obtain and maintain the

desirable characteristics obtained during the former tests. The methods used to characterize the materials can easily be adapted to quality control of incoming materials. Not all the tests run at time of characterization need to be done for incoming receiving inspection; however, tests should be selected that would adequately fingerprint the material. A brief description of the test methods used follows:

- Thermal gravimetric analysis (TGA). This method plots weight loss of the material against time or temperature in a controlled atmosphere.
- Differential scanning calorimetry (DSC). This method measures quantitatively any thermodynamic changes that occur in the material with time or temperature.
- Dielectrometry (Tan δ). This method continuously measures certain electrical properties of material with changes in temperature. The particular electrical properties measured are capacitance, conductance, and dissipation factor. In this test the dissipation factor is very sensitive to chemical changes that occur in the material.
- Pyrolysis gas chromatography (PGC). This is a Boeing-developed method that quantitatively separates and fingerprints the low fractions and then finger prints the remaining portion by pyrolizing it on the gas chromatograph.
- Gas chromatography-mass spectrometry (GC/MS). This method separates out the components that volatilize under 200°C and identifies them by a computerized search based on the mass spectrum.
- Fourier transform spectroscopy (FTS). This is infrared analysis of the material.
- Solids analysis. Instrumentation used for this analysis includes energy dispersive X-ray, microprobe, and emission spectroscopy, which identify elements present. The X-ray diffraction method is used to identify crystalline components present. Atomic absorption is used for quantitative analysis of elements present.

- High pressure liquid chromatography (LC). This test has several modes, which operate on two different principles. One mode separates the resinous portions of the material by its molecular weight distribution. The other mode separates the material by its functionality or polarity. Thin-layer chromatography also aids in optimizing this method.

6.1.5 Material Used in Aerospace Systems. Encapsulating materials that have demonstrated good performance in electronic applications are shown in Table 34. Each of these materials has its limitations and must be evaluated for operating temperature range, thermal coefficient of expansion, and compatibility with parts within the module.

A quick literature survey will also reveal many products that appear right for a particular application because some reliable manufactures have used the material. Often the user of a material modifies the formulation to suit his need, which may change one or more of the properties of the original mixture. When a user is successful with a specific formulation, it may be placed on the market. Such materials are shown in Table 34. Some of the materials have been characterized, and their properties can be found in References 152 through 157.

6.2 Processes. Encapsulation of a material means completely embedding or encasing an electrical assembly in a 100 percent reactive liquid insulating material using a process that achieves the highest degree of void-free insulation.

6.2.1 Processing. Processing involves everything from cleaning the circuitry to be potted to mixing, pouring, curing, and post-curing the encapsulant.

Cleaning the molds and circuits to be potted is critical. Some rules follow (Reference 158).

- Work tables to be used in this process should be covered with

TABLE 34

PERFORMANCE OF INSULATING MATERIALS AT LOW TEMPERATURES AND 10^{-4} N/cm^2 PRESSURE

Material	Working Voltage	Temperature	Comments
Conap	3000 Vrms	-55 to 125°C	No damage
Solithane 113/300 Formula 12	15 kV	-40 to 85°C	Successful
Scotchcast 280/281	3000 Vrms	-40 to 125°C	Successful for Transformers
RTV 615	20 kV	-55 to 85°C	Successful
615A	15 kV	-20 to 85°C	Successful
Adriprene	5 kV	-40 to 85°C	Successful
PR 1538	5 kV	-40 to 85°C	Successful
DC 93-500	15 kV	-40 to 85°C	Successful
RTV 3140	1.5 kV	-40 to 85°C	No Damage
RTV 11	4.5 kV	-40 to 85°C	Successful
Formulated Epoxy	10 kV	-40 to 85°C	Successful
Uralene 5753LV	10 kV	-40 to 85°C	Successful
Epon 825	10 kV	-55 to 85°C	Successful
DC 170	10 kV	-55 to 110°C	Successful

a clean plastic or paper cover during assembly of the component into the mold

- New molds shall be solvent washed and vapor degreased in methyl chloroform to remove oils and other foreign materials. Heat the mold to 168±8°C.
- Spacers molded of the same material or a material compatible with that used in the encapsulated assembly will be used frequently to maintain required dimensions between the components and the mold faces. These spacers shall be cleaned with inhibited methyl chloroform.
- All visible flashing and contamination should be removed from recycled molds by brushing and scraping. Use only wooden, plastic, or brass scrapers. Care must be taken to avoid scratching or nicking molds during flash removal.
- The unit to be assembled into the mold should be handled carefully to avoid damage to the components in the unit or to lead wires, and to prevent introduction of any foreign material, mold release, or other contaminants.
- Adhesive tape should be applied to the mold parting lines. If tape does not provide a complete seal, a coating of silicone rubber shall be applied.
- Teflon surfaces should be treated with Teflon etch solution and the component assembly to be impregnated shall be vapor degreased. The mold and component assembly shall be prebaked at 135±5°C to remove all moisture in accordance with Table 35.

TABLE 35

PREBAKE SCHEDULE

Component Assembly Weight	Baketime
0.25 lb and less	2 to 2.5 hours
0.26 to 5 lb	4 to 4.5 hours
5.1 to 25 lb	8 to 8.5 hours
Greater than 25 lb	12 to 12.5 hours

- The mold and assembly then should be transferred to another oven and baked at 70±5°C for 2.25 hours. Transfer the assembly immediately to the vacuum potter.
- The assembled molds should be evacuated to a pressure of 0.5 mm of mercury or less, and maintained at that pressure for a minimum of 30 minutes.

6.2.2 Parts and Circuits Cleaning. Scrub solder joints and other areas contaminated with hard-to-remove deposits of foreign matter using a stiff, short-bristle brush wetted with isopropyl alcohol. Then thoroughly clean all areas to be potted with fresh solvent. Allow the solvent to completely evaporate before proceeding with the next operation.

6.2.3 Vacuum Impregnation. The basic and foremost objectives during impregnation of parts is to replace all cavities with the encapsulant and have a completely void-free, crack-free material. To achieve maximum filling, it is usually necessary to reduce the encapsulant viscosity. Application of heat reduces viscosity, but the reaction rate also increases, thereby shortening the potlife. To determine the optimum minimum viscosity, the mold and part temperature can be increased to a value determined by experiment. Heating the parts is preferred instead of heating either the as-mixed material or the premixed components, where the degree of cure is more difficult to control.

6.2.4 Potting. As soon as the encapsulant is mixed, it should be placed in a vacuum and outgassed to remove all extraneous gases. Then the material can either be poured into the mold and the mold evacuated followed by pressurization, or it can be siphoned into the mold inside the vacuum chamber. The potting material is drawn by the vacuum inside the chamber by opening a clamp in the siphon that is immersed in the encapsulant. The vacuum must be maintained at all times during this process to eliminate gases.

Removal of trapped air is mandatory for producing void-free potting. Either vacuum exposure after liquid filling or liquid flowthrough molding can be used. Vacuum molding is less sophisticated in that just a simple box mold

can be used. Flowthrough molding requires critical tooling for proper location of inlet and exit openings and proper pressure application, and usually requires some sort of automated meter mixing.

The time of vacuum exposure is critical because too short a time leaves entrapped voids and too long a time may remove the catalyst and alter the properties of the cured material or might possibly prevent cure.

Over pressurization with dry nitrogen is used after evacuation to promote flow and filling of potting material into deeply buried voids. Too little pressure would be ineffective and too much pressure could force nitrogen back to cause void areas.

Each material has its own unique cure time and temperature requirements. These values must be honored for best results.

After the assembly is removed from the mold and inspected for blisters and voids, it should be post-baked to relieve mechanical stresses within the encapsulant. Post-baking may require temperatures to 150°C for 96 hours to meet all outgassing requirements.

6.2.5 Viscosity. The importance of low viscosity for encapsulating materials cannot be over emphasized. Viscosity relates to the ability of the encapsulating material to thoroughly fill all the interstices in high voltage assemblies, and to thoroughly impregnate critical, tightly wound coil devices such as transformers, the wells around connector pins, and the small gaps between the parts and boards on printed circuit boards. The use of low viscosity encapsulating resins simplifies vacuum-pressure processing, which is one of the critical factors in achieving a high yield, high reliability encapsulated, high voltage electronic assembly.

6.2.6 Pot Life. Pot life is another important encapsulating material characteristic. Pot life is the time the encapsulating material retains a low viscosity during the encapsulation process. Thus, the considerations with respect to internal voids apply to pot life as well as to viscosity. It is desirable

to have a long pot life; that is, to retain low viscosity during the complete processing cycle. If the encapsulating material gets thick too quickly, voids are produced during the encapsulation process.

6.2.7 Adhesion of Encapsulating Materials to Components. This characteristic of encapsulating materials is also important for encapsulation of high voltage electronics. Lack of adhesion leads to debonding and air voids, thereby initiating partial discharges or arcing and tracking problems. Epoxy encapsulating materials have excellent adhesion properties. Silicone encapsulating materials do not have good adhesion alone, but can be made to exhibit good adhesion to varying degrees when suitable primers are applied to components in a controlled process.

6.3 Process Variables. Important processes parameters that should be considered when a material has been selected are included in the process variables plan developed in Table 36. This table shows the combination of process variables used during a particular experimental run. The high level variation values for a parameter are shaded. These parameters were chosen for the initial process variable study because they are directly related to filling the interstices in a densely wound coil. The following sections contain the rationale used in selecting the process study parameters.

6.3.1 Mold and Part Pre-Heat Temperature. To achieve maximum filling, it is usually necessary to reduce viscosity. Application of heat reduces viscosity but the reaction rate is also increased, thereby shortening the pot life. To determine the optimum minimum viscosity, the mold and part temperature can be varied. This technique is used rather than heating either the as-mixed material or the pre-mixed components, where degree of cure is more difficult to control.

6.3.2 Vacuum Time. Removal of trapped air is mandatory for producing void-free potting. Either vacuum exposure after liquid filling or liquid flowthrough molding can be used. Vacuum molding is less sophisticated in that only a simple box mold can be used. Flowthrough molding requires

TABLE 36

POTTING VARIABLE COMBINATIONS FOR A SILASTIC MATERIAL

FACTOR STUDIED	MOLD AND PART PREHEAT TEMP	VACUUM TIME	OVERPRESSURE (PSI)	OVERPRESSURE TIME
Base Level	100°F	10 min.	45	30 min.
Unit of Variation	30°F	5 min.	30	25 min.
High Level	130°F	15 min.	75	55 min.
Low Level	70°F	5 min.	15	5 min.
SAMPLES				
A, B	70°F	5 min.	15	5 min.
C, D	130°F	15 min.	15	5 min.
E, F	130°F	5 min.	75	5 min.
G, H	70°F	15 min.	75	5 min.
J, K	130°F	5 min.	15	55 min.

critical tooling for proper location of inlet and exit openings, proper pressure application, and some sort of automated meter mixing.

The vacuum exposure time is critical because too short a time leaves entrapped voids and too long a time may remove the catalyst and alter the properties of the cured material, or might possibly prevent cure.

6.3.3 Overpressure. Overpressurization with dry nitrogen is used after evacuation to promote flow and filling of potting material into deeply buried voids. Too little pressure would be ineffective and too much pressure could place nitrogen back in some void areas.

6.3.4 Overpressure Time. There is optimum time for the application of over pressure. Too short a time will not provide enough flowtime for proper filling. Too long an overpressure time is inefficient.

The above four process variables were selected because of their importance in completely filling densely wound coils. Other important process parameters which are held constant include:

- Dip priming
- Primer cure time and humidity
- Resin cure time

It may become apparent that the combination of longer vacuum time (15 minutes), higher overpressure (75 psi), and longer overpressure times (55 minutes) produce 100 percent filling. However, test samples with 100 percent filling may have poor partial discharge corona inception and extinction CIV/CEV values. Then a decision has to be made to evaluate different primer application techniques and different primer curing conditions. This can be accomplished in conjunction with the process parameters, which produce 100 percent filling. All previous transformers should be primed and cured in a constant relative humidity oven at constant temperature. By following these procedures the process parameters can be

selected that produce 100 percent filling. An example of 100 percent filling for the samples of Table 36 are:

- Mold and part preheat, -70°F
- Vacuum time, -15 min
- Overpressure, -75 psi
- Overpressure time, -30 min

6.3.5 Adhesion. Electrical and electronic modules contain a variety of different components. These different electronic components are encased in a variety of materials such as ceramics, plastics, metals, platings, paints, and markings. Often it is difficult to determine the exact nature of the parts surface (i.e., are mold releases still present; what marking inks are used; etc.). To determine the effectiveness of the encapsulant, determination of its adhesion to these various possible substrates is required. Adhesion can be determined for a material in contact with different parts, as shown in Table 37. Three sets of parts were tested, each with a different cleaning and priming operation. The first set was not cleaned. This would correspond to normal hand-assembled packages. The standard dip priming in RTV 1200 primer was used for the silastic encapsulant. The second and third sets were cleaned by the standard vapor degreasing, vacu-blasting, and isopropyl- alcohol wash. Set B was dip primed and Set C was spray primed. This was accomplished to determine the best method of applying primer to the proper thickness. Dip coating yields a constant but thick coating. Spray priming permits a thinner coating of primer to be applied.

Table 37 shows the results of the adhesion test. Because of the geometry of the parts, most tests were pull tests and some were peel tests. However, all three like parts were tested the same way to make a valid comparison of the differing cleaning and priming operations. All parts with leads had the leads on one side removed and were potted in tube or dish containers with the leads extending above the potting surface for gripping during test. The bobbins were potted to just one surface. Silastic bonding to other materials test results are provided in Table 38.

TABLE 37

SILASTIC ADHESION TEST RESULTS

PART TYPE	SURFACE MATERIAL	POUNDS OF FORCE EXHERTED: SET A — NO CLEANING, DIP PRIMED	SET B — NORMAL CLEANING, DIP PRIMED	SET C — NORMAL CLEANING, SPRAY PRIMED
1. Bobbin	Epoxy-glass Laminate	8 pounds per inch width peel	5 pounds per inch width peel	7 pounds per inch width peel
2. Bobbin	Delrin	1 lb. per inch width peel	5 lb. per inch width peel	6 lb. per inch width peel
3. Bobbin	Acetal	20 lb. per inch width peel	16 lb. per inch width peel	22 lb. per inch width peel
4. Ferrite Core	Sintered Steel	4 lb. per inch width peel	4 lb. per inch width peel	5 lb. per inch width peel
5. Dual Inline Package	Gold Plate	40 lb. pull in shear	---	42 lb. pull in shear
6. Dual Inline Package	Aluminum Oxide Ceramic	---	26 lb. pull in shear (Leads broke)	[illegible].5 lb. pull in shear (Leads broke)
7. Dual Inline Package	Filled Phenolic	23.5 lb. pull in shear	25 lb. pull in shear	21 lb. pull in shear
8. Carbon Composition Resistor	Painted Phenolic	20 lb. pull in shear	29.5 lb. pull in shear (Leads pulled from part)	26 lb. pull in shear (Leads pulled from part)
9. Wire Wound Resistor	Mylar Tape	37.5 lb. pull in shear (Leads broke)	29 lb. pull in shear (Leads broke)	77 lb. pull in shear (Delaminated part)
10. TO-5 Transistor	Nickel Over Kovar	23 lb. pull in shear (Leads pulled from part)	50 lb. pull in shear	45 lb. pull in shear
11. Radial Lead Capacitor	Filled Epoxy	37.5 lb. pull in shear	29 lb. pull in shear (Corner tear)	34 lb. pull in shear
12. TO-99 Operational Amplifier	Bright Tin Over Kovar	78 lb. pull in shear	60 lb. pull in shear	[illegible] lb. pull in shear (Corner tear)
13. Axial Lead Capacitor	Molded Silicone	25 lb. pull in shear (Lead broke)	30 lb. pull in shear (Lead broke)	25 lb. pull in shear (Lead broke)
14. Diode	Glass	15 lb. pull in shear	---	13.5 lb. pull in shear
15. Wire	Kapton	13 lb. pull in shear	22.5 lb. pull in shear	25 lb. pull in shear
16. Wire	Silicone	13.5 lb. pull in shear (Neck down peel)	13 lb. pull in shear (Neck down peel)	12 lb. pull in shear (Neck down peel)
17. Metal Film Resistor	Epoxy	19 lb. pull in shear	16 lb. pull in shear	16 lb. pull in shear

TABLE 38

SILASTIC BONDING TEST RESULTS

1.	Silastic E bonded to primed Parylene over gold plate	1.4 pounds per inch width - 90^{o} peel strength
2.	Silastic E bonded to primed Parylene over tin plate	1.8 pounds per inch width - 90^{o} peel strength
3.	Silastic E bonded to primed etched teflon	6 pounds per inch width - 90^{o} peel strength
4.	Silastic E bonded to primed polyester-amide coated magnet wire	32 pounds pull
5.	Silastic E bonded to unprimed polyester-amide coated magnet wire	15 pounds

The results of the tests shown in Tables 37 and 38 indicate that the Silastic has excellent adhesion to most components and power supply parts. Adhesion to bobbins of epoxy-glass and Delrin, and ferrite core material is low but adequate. Proper cleaning procedures can provide a marked improvement (e.g., Delrin, and nickel plate over kovar). It is concluded that properly cleaned and primed parts, either sprayed or dipped, can be adequately bonded to a Silastic potting compound. Bonds between some Silastics and Parylene are marginal and not recommended. Bonding of some Silastics to Teflon can be accomplished if the Teflon is first etched with sodium metal/ammonia.

6.3.6 Storage and Handling Controls Development. Materials and process controls are necessary to ensure that materials are of proper quality and are properly used. Normally these controls include such techniques as infrared and ultra-violet analysis, specific gravity, hardness, and viscosity. Viscosity measurements are easily obtained and can provide information on the age of a material and its processability. Pot life of a polymerizing resin is usually defined in terms of a maximum viscosity that can be processed.

Viscosity is defined as that property of a fluid material which is a measure of resistance to flow. Newton hypothesized that the magnitude of the force required to overcome viscous resistance is directly proportional to the rate at which the fluid is sheared. As knowledge of viscosity increased, it became apparent that Newton's hypothesis fit only a limited number of fluids. This class of fluids is referred to as Newtonian. The larger class of materials is referred to as "non-Newtonian," where proportionality between applied force and shear rate does not exist.

Non-Newtonian fluids have been further classified: Bingham plastic fluids, pseudoplastic fluids, dilatant fluids, thixotropic fluids, and rheopectic fluids. Gels are Bingham plastics, polymer solutions and some high molecular weight silicones are pseudoplastics, thick starch-water suspensions are dilatant fluids, mayonnaise is a thixotropic fluid, and bentonite sols are rheopectic fluids. Each class of non-Newtonian fluid behaves differently as the shear rate through the fluid is varied.

Comparative viscosities taken at a constant shear rate can provide useful information on a particular fluid; however, a variation of 1°C can produce a 10 percent variation in viscosity value for non-Newtonian fluids. Thus use of viscosity for materials control must be accomplished with caution for most fluids.

A viscosity study on the Silastic material, a pseudoplastic, was initiated to determine the effectiveness of this property for use in process control. Three different lots of the Silastic material were used: one lot was new, one was 6 months old, and the other was 2.5 years old. Viscosity measurements were made on the base resin versus temperature to determine age effects. Measurements were then made on mixed viscosity versus time to determine pot life.

Three different batches of the Silastic material that were studied are:

- Batch #1, new material received 12/77 (new)
- Batch #2, 6-month-old material received 6/77 (6 months old)
- Batch #3, 2.5-year-old material received 3/75 (2.5 years old)

The third batch had two different storage conditions.

- Batch #3-A, room temperature storage loosely covered for 2 months
- Batch #3-B, outdoor storage in original 25 gallon container

The first study was to determine the effect elevated temperatures had on the base resin. Measurements were made using a Brookfield Viscometer Model RV with spindle #6 at 4 r/min. The results are shown in Table 39.

The second study was made to determine how the mixed catalyst and base viscosities vary with time for different age materials. Figure 92 shows the results of this study. Similar studies, analyses and tests should be made for materials selected for aerospace application.

TABLE 39

EFFECT OF TEMPERATURE ON VISCOSITY

	Batch #1	Batch #2	Batch #3A	Batch #3B
70°F	1,850	2,075	1,588	1,000
100°F	1,250	1,500	950	675
150°F	1,060	1,200	625	550

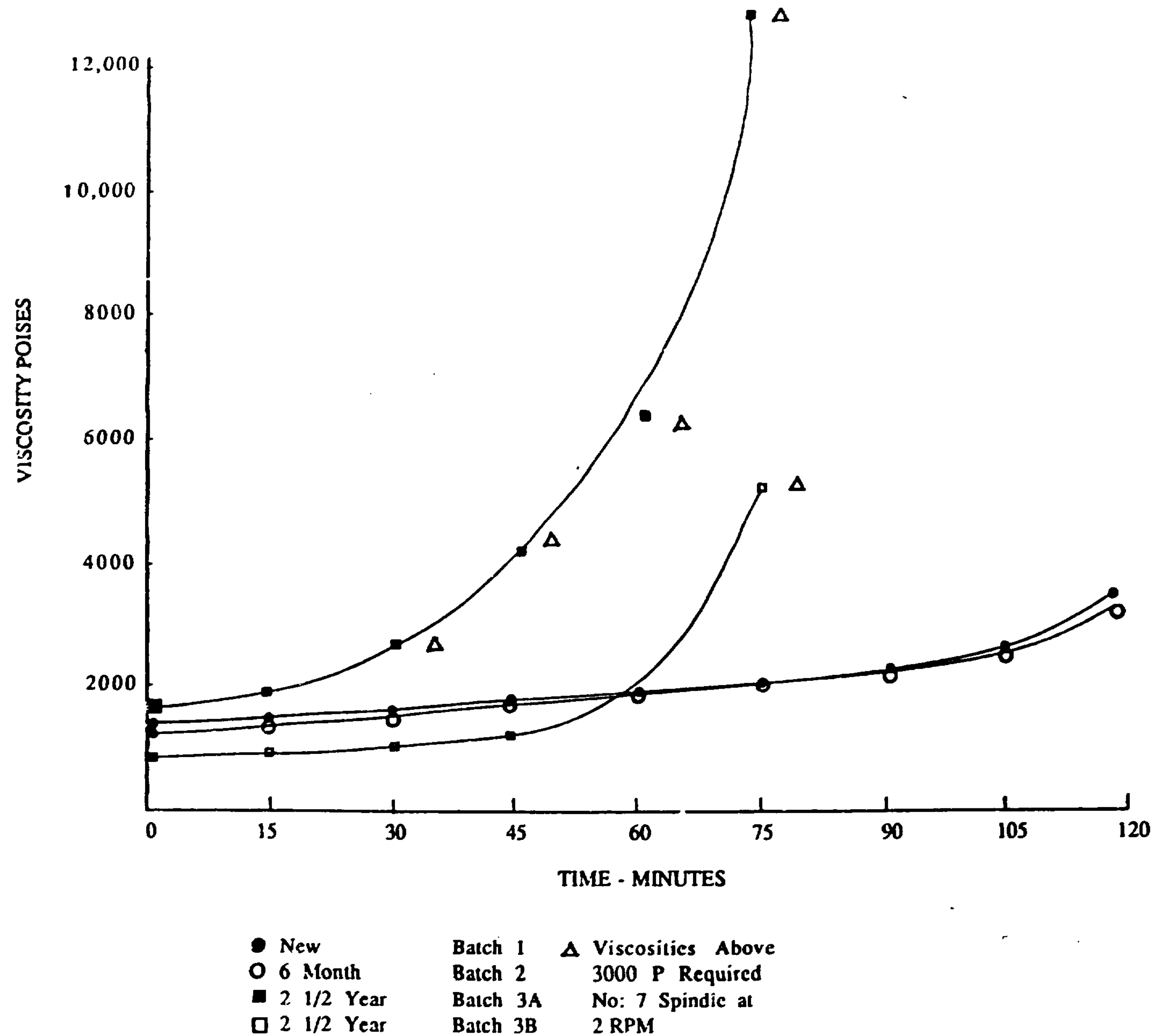

Figure 92. Mixed Viscosity for a Silastic Material Vs. Time

SECTION VII
MANUFACTURING

Regardless of the excellence in electronic design, material and processes evaluation, and packaging of high voltage systems, the power supply will not perform reliably if manufacturing controls are not maintained to ensure that the power supply is properly assembled, fabricated, and tested. The main considerations in proper manufacture are:

- Contamination and cleanliness
- Accuracy in all physical measurements and other aspects of processes such as weight, volume, time, temperature, pressure, and material control
- Thorough knowledge of all aspects of incoming process controls and materials processing

7.1 Yield. Most manufacturers consider yield with minimum repair as the most important fabrication criterion. In general, this matches the very important criterion that the insulating material thermal properties be matched to the power supply parts thermal and dimensional properties. Thus, use of a high-performance ruggedized material is mandatory, as well as control of electrical stress in the material. This is why hard filled epoxies with good thermal characteristics are often used to encapsulate small submodules. Following encapsulation, the submodules are interconnected and the assembly potted in a soft repairable material. Interconnections must be flexible, with stress relief bends. For good power supply fabrication, the end product must be efficient and competitive in cost. This implies that manufacturing yield is a two-part program: (1) the manufacture of the components, structures, and parts; and (2) the final assembly, test, and acceptance of the power supply. Efficiency is defined as the actual time to manufacture divided by the time allocated to manufacture a product. Yield is the number of power supplies produced compared to the number placed into production. Some problems associated with manufacturing are detailed in this section.

7.1.1 Tooling. Some problems associated with tooling for electrical insulating materials that must be overcome to increase efficiency include:

- Mold release contamination
- Chipping of materials as they are removed from the mold
- Excessive grinding and smoothing required for encapsulated components because of tooling surface roughness
- Wire breakage on small, high voltage transformers due to misalignment
- Contaminated mixing crucibles
- Improper cleaning of tools
- Equipment controls
- Workmanship

Properly developed and designed tools are essential for the technical personnel to perform their duties so that high yield can be achieved It is equally important to train each technician in the correct operation and use of these tools.

7.1.2 Assembly. Many problems must be overcome during assembly. Typical problems are:

- Solder joints. When solder balls are required, the ball must be made after the joint is complete and inspected. The ball must not degrade the solder joint.
- Wiring. Twisted wires and wires randomly placed in a high voltage circuit between modules can be subjected to high electric field stress causing shorts and arcs.
- Wires for high-altitude application must be outgassed during encapsulation to prevent air pressure buildup at the end of the wire when the unit is in flight.
- Movement of wires during encapsulation.
- Poor bonding to waxed or contaminated parts.

- Contamination by grease and debris from the part supplier or by the assemblers.
- Use of tabs which entrap air in transformers.
- Use of tabs with non-compatible bonding material.
- Loose wraps and ties.
- Overtightening of circuit board mounts, causing board breakage or splitting.
- Use of screws in boards or plastics with air gaps at the end of the screws.
- Use of sharp-edged high voltage parts next to low voltage circuits and grounds.
- Use of chassis with sharp edges or burrs.

Many of these items should be rejected by quality control before potting or immersion in an oil. It is difficult to inspect for these things, after potting in a colored or opaque material.

7.1.3 Quality Control. Quality control engineers should coordinate their efforts with the power supply electronic and packaging design engineers to obtain a more complete technical knowledge of all engineering specifications. An effort should be made by the power supply engineering design team to develop common standardized specifications and procedures. The design engineers must determine the minimum standards that can be achieved by quality control before the design is released to manufacturing. After a new development prototype assembly is developed, the high voltage designers should spend several hours coordinating with quality control, detailing critical component inspection, and outlining pass/reject criteria and who to call for immediate consultation.

7.1.4 Testing. Yield and manufacturing efficiency can be improved with proper testing and test equipment. The following tests should be required for all designs:

For magnetic devices:

- Continuity tests before and after encapsulation.
- Corona test after potting to determine insulation integrity between coils, between coils and cores (if available), and between turns within a winding.
- Parts burn-in, where burn-in is required.
- Out-of-tolerance tests. High voltage components may be in tolerance at low voltage but fail at high voltage. High voltage testing is preferred.

For assembly:

- Assembly continuity tests.
- Material characterization tests.
- Material viscosity tests to indicate aging or formulation changes.
- Final assembly tests to determine operation at ambient, altitude, and high and low temperature.
- Electrical high voltage tests: insulation resistance, dielectric withstanding voltage tests, and partial discharge tests.

Many inferior and out-of-tolerance parts have been found and rejected by imposing the proper test program to the parts and modules before final assembly. This results in better yield and lower cost.

A long list of tests has commonly been used to evaluate chemical makeup and material properties of encapsulation materials before and after cure. This list of tests varies from one company to another depending on the type and amount of analytical chemistry instrumentation and physical test equipment available. The influence and effectiveness of the quality control organization within a given company often determine the extent and type of testing conducted. Test equipment and personnel availability typically limit the capability of some companies to conduct minimal tests to characterize encapsulation materials and verify the materials' consistency from batch to batch. Tests typically run to characterize the material properties of incoming encapsulation material consist of:

- Visual inspection
- Specific gravity
- Viscosity
- A method to verify cure, i.e., hardness or gel time

Other chemical and physical properties of the material are generally accepted as those values originally designated from the vendor or from developmental test results. Routine test analysis of the material in use is not possible because of the lack of personnel and necessary test equipment.

Companies with adequate experience in testing can perform extensive chemical characterization and physical testing of encapsulation materials. Test equipment is available generally under the control of a quality assurance group. Tests for material verification and characterization, in addition to those listed previously, include the following:

- Infrared spectroscopy
- Ultraviolet spectroscopy
- Liquid chromatography
- Gel permeation chromatography
- Thermal gravimetric analysis (TGA)
- Differential thermal analysis (DTA)
- Differential scanning calorimetry (DSC)
- Dielectric strength
- Dielectric constant
- Arc resistance
- Volume resistivity
- Surface resistivity
- Solids analysis
- Adhesion tests

Some of these test methods are complementary, i.e., they provide much the same type of information. Thus, even a large company would not be expected to use all these tests.

Most companies use many of these test methods. Most commonly used tests are adhesion tests, solids analysis, and electrical properties tests. Instrumental test methods, relating material changes relative to temperature, most used are TGA, DSC, and DTA. Analytical chemistry techniques are less used partly because of the expense of the instrumentation and the requirements for specialized personnel. The companies, that use analytical instruments use all of those listed for some phase of material analysis.

7.1.5 Reliability. Reliability and repairability can be improved in two ways: (1) by selecting void-free encapsulating materials that properly bond to all parts and boards within the power supply at all operating temperatures, and properly processing the electronic circuit parts and materials, and (2) by analyzing the circuit for faulty parts, high electric-field stress near the insulated connections, and parts, and providing proper heat transfer. Each is equally important to obtain a high-quality, cost-effective power supply with high reliability.

Insulation failures leading to low MTBF fall into four categories: (1) high electric stress (packaging); (2) selection of parts or improper use of parts (design); (3) poor bonds and board delamination (material); and (4) voids, cracks, workmanship, and handling (processes). These items are evaluated in Table 40.

TABLE 40

SUMMARY OF FAILURE ANALYSES FROM INDUSTRIAL AND GOVERNMENT SURVEYS

ITEM	PERCENTAGE
Materials	15
Packaging	24
Design	25
Processes	36

7.2. Government and Industrial Survey. Questionnaires were distributed to government and industrial agencies asking for information on questions on materials defects, encapsulation, packaging, electronic design, processes, and testing. Each question had several subtopics to enable a flexible response to the problem areas associated with low yield and high life cycle costs. The greater number of responses identified packaging and processing for improvement. Specific problem areas identified were wire routing and component and conductor spacings; differential thermal expansion of parts, metals, and resins; and cracks and voids caused by poorly applied primer or contamination. Testing was another source of concern. Most responses identified test materials electrical properties of resistivity, partial discharge, and dielectric strength, but few checked on the mechanical or electrical properties.

Another surprising response was on the subject of encapsulation. Most responses agreed that vacuum potting is required to remove entrapped gases that result in voids, but only half the responses showed use of overpressure after the vacuum impregnation. This could be a source of voids in the more viscous materials used in transformers and tightly packaged parts. The major material and process related sources of failure gathered from the surveys for encapsulated high voltage power supplies are described in the following section.

7.2.1 Material Sources of Problems. Problems related to materials selection and application are:

- High-viscosity resins
- Short pot life resins
- Poorly adhering resins and difficult-to-bond surfaces
- Primers
- Poor compatibility of materials
- Low thermal conductivity resins
- High thermal expansion resins
- Inadequate thermal stability of resins
- High shrinkage resins

- High internal stresses in resins
- High outgassing materials
- Poor thermal shock resins
- High electrical loss resins.

7.2.2 Process Sources of Problems. Problems associated with materials processing are.

- Mixing procedures
- Cleaning and cleanliness control
- Application of primers
- Vacuum-pressure cycles
- Evacuation of resins
- Pre-drying of materials and parts
- Post-baking of encapsulated assemblies

Several questions were devoted to power supply insulation. Most responses agreed that power supplies with outputs less than 2500 W and 10,000 volts can be successfully potted. Higher power units and higher voltage units used potted modules or parts such as transformers with oil or liquid for the main insulation. These techniques give much better thermal control and stability to the critical electronic parts and materials. The problems, their cause, and their solutions are shown in Table 41.

7.2.3 Materials and Processes Survey Conclusions. An analysis of the response led to the following general conclusions. Materials problem areas, in order of contribution to low MTBF and high life cycle costs, are:

- Differential thermal expansion of resin and electrical and mechanical parts during cure
- Selection of materials based on thermal expansion, adhesion, and workability
- Cracking during temperature cycling
- Contamination of materials within the working area and by combinations of materials within a power supply

TABLE 41

ANALYSIS OF CRITICAL MATERIAL AND PROCESS RELATED FAILURES ON ENCAPSULATED HIGH VOLTAGE POWER SUPPLIES

Yield and/or Reliability Problem	Discussion of Problem	Related Material and/or Processing Factors
High voltage electrical failure of optical coupler occured in vacuum testing.	In the failure analysis of this defect, it was found that failure occurred due to mold release residue found on the epoxy housing. The assembly was locally repaired by cutting away potting material, cleaning and repriming the housing surface, and repotting.	Process cleanliness and control is the critical factor. This also relates to handling of mold releases and to the use of primers for obtaining adhesion of potting compound to housing surfaces.
Arcing from high voltage wire occurred in vacuum testing.	Failure analysis revealed that a cover screw which was no longer to be used had been assembled by mistake and then removed after the potting was partially cured, leaving a void in the potting material. The assembly was locally repaired by cutting away potting material, cleaning, repriming and repotting.	The void is the potting material was the major responsible factor. This void was caused by error rather than by inadequate potting procedure.
An arc occurred between printed circuit board connectors after 1 1/2 days in vacuum with high voltage turn-on.	Arc caused failures on low voltage board, and left a carbon track on the potting material in an area where there was no primer, and hence no adhesion. The primary process and controls were improved, The assembly was locally repaired by cutting away potting material, cleaning, repriming, and repotting.	Process optimization and control for use of primers is the cirtical process factor. Also involved is arc and track resistance of insulating materials.

TABLE 41 (contd)

Yield and/or Reliability Problem	Discussion of Problem	Related Material and/or Processing Factors
Frequent voltage breakdown in a 25 kV power supply which is potted in silicone rubber potting material. Also, arcing was observed.	Review and analysis of this problem led to the conclusion that packaging configuration was too tight, causing leakage between closely spaced components. Changes made included some redesign and layout of packaging, including partitioning, and tightened process controls.	Since space requirements can require tight packaging configurations, closely controlled potting and encapsulation processes are required. Also packaging design should take into account the important material and processing limitations.
Voids and separation of potting material from potting case were constantly found in purchased high voltage power supplies.	Reviews with supplier indicated use of a high viscosity silicone potting compound, along with a lack of control in the vacuum potting process. Also, high thermal expansion of the potting compound led to separation of potting material from potting case. Solution to this problem was use of a lower viscosity, lower thermal expansion potting compoung, and tightened controls on vacuum potting process.	Critical material and processing factors are viscosity of potting compound thermal expansion of potting compound and control of vacuum potting process.
Recurring corona leakage in high voltage power supply potted in RTV 11 silicone rubber.	Corona leakage was found to occur at either the phenolic box to potting material interface or component to potting material interface. Poor adhesion to potting material to other surfaces was determined to be the major problem.	Poor adhesion of silicones to other surfaces is the major material and processing problem. Moisture absorption into the phenolic case was also considered to be a possible problem source.

TABLE 41 (concluded)

Yield and/or Reliability Problem	Discussion of Problem	Related Material and/or Processing Factors
An opening occurred in the high voltage transformers of two 2 KV high voltage power supplies during thermal vacuum testing.	The open area was caused by work hardening of copper wire due to differences in thermal expansion between the epoxy encapsulant and the fine wire. This break created a small void, allowing ionization at high voltage, which resulted in formation of carbon tracking.	This problem relates to the high thermal expansion of many encapsulating materials, and the low-arc and track resistance of these materials.
High voltage power supply failure occurred during launch due to inadvertant power turn-on during the fuel dump.	High voltage turn-on ignited a fuel cloud, causing an explosion and damaging spacecraft components. High voltage terminals were exposed, rather than encapsulated.	Encapsulation of exposed high voltage terminals was used for future systems, along with current limiting resistor networks.
Corona occurred in high voltage transformer during thermal vacuum testing.	Analysis indicated likely cause of problem to be voids in the encapsulating material due to insufficient outgassing of the epoxy prior to cure.	The related material and processing problem is inadequate evacuation of the catalyzed encapsulating material during the vacuum cycle.
Open circuits developed in the interconnection between diodes in an encapsulated high voltage diode stack.	Indications were that the opens were caused by *high thermal expansion* of the potting material. Localized air spaces developed, leading to high voltage ionization in the voids, and occurrence of carbon tracks which shorted out individual diodes and eventually caused voltage breakdown of the stack.	Critical problems are thermal expansion properties and arc and track resistance properties of encapsulating materials.

- Resin shrinkage
- Start cure time
- Filler separation during encapsulation by sieving in wound devices

Material problems of a secondary nature which relate primarily to material selection and handling are listed as follows:

- Debonding at high temperatures
- Poor thermal conductivity
- Incompatibility of circuit materials and resin
- Reversion of materials when subjected to heat or humidity
- Materials aging due to long storage or improper storage
- Dielectric heating at high frequencies

Very few problems are associated with dielectric strength and dielectric constant of the selected materials.

Filled and unfilled silicones and urethanes were selected more often for electronic modules and for power-supply potting. Maintainability and repairability were the better reasons for their selection. In addition, the clear or opaque silicones and urethanes were selected for ease in locating faults and shorts within a module.

7.2.4 Packaging and Design. Wiring, conductor and termination spacing, and thermal control are the major packaging problems, with some emphasis on contamination and placement of heat sinks. Selection of electronic and mechanical parts and printed circuit board layouts appear to be the other design and packaging problem areas. Wire spacing can change significantly because of improper staking or bundling. All high voltage wires require special attachment to prevent movement during the cleaning and encapsulation processes.

A list of the packaging and manufacturing related defects that result in low yield and high life-cycle costs for high-voltage power supplies follow. The problems with greatest frequency head the list.

- Difference in coefficient of thermal expansion of parts, boards, ground planes, metals, and resins
- Wire routing
- Conductor spacing
- Teflon adhesion
- Solder joints and points rather than solder balls
- Contamination during assembly
- Heat sink size and placement; lack of heat sinks in the design
- Printed circuit board conductor spacing
- Resin and filler formulation and separation
- Shielding between high voltage and low voltage circuits
- Conductor diameters
- Mechanical stress relief on parts terminals and leads
- Moisture
- Resin selection

A list of electrical and mechanical design-related defects that contribute to low MTBF and high life cycle costs are:

- Transformer insulation design for leads, terminations, and coils
- Component overheating
- Selection of capacitors, resistors, diodes, solid-state devices, integrated circuits, wire coatings, and transformer core design material and configurations
- Voltage derating of capacitors and power derating of resistors
- Selection of standoff materials and configurations
- Selection, shaping, and application of fiber, paper, films, and tapes
- Wire breakage: inadequate stress relief
- Selection of semiconducting layer around high voltage conductors. This technique is being considered for the higher voltage units over 30 kV.

7.2.5 <u>Manufacturing Processes</u>. Wetability, improper mixing and application of materials (including primer), and use of multiple dielectrics affect the

encapsulating material processing most. These items, if not compatible with the parts and dielectrics, result in voids and cracks and the mechanical stressing of wiring and joints within the power supply following encapsulation. These features should be examined carefully and included in the process specification for high voltage power supplies. In addition, the encapsulated materials should be subjected to electrical and visual tests to examine the finished product for these failure mechanisms before and after the thermal and shock tests.

A list of materials processing related defects which result in low yield and low MTBF are listed below. Most frequent problems are at the top of the list.

- Voids or cracks
- Poorly applied primer
- High viscosity
- Insufficient wetability
- Improper mixing procedure
- Contamination
- Electrical joints subjected to mechanical stress from thermal expansion and contraction of resins--solder pull
- Complex molds
- Use of epoxies and silicone resins in the same power supply
- Incomplete thermal-vacuum pressure cycles
- Insufficient pot life
- Lack of lead stress relief
- Single-sided printed circuit board tracers subject to damage through lifted pads
- Mold release contamination
- Improper humidity control during cure
- Uncontrolled temperature during thermal vacuum potting

7.2.6 Testing. Partial discharge, dielectric strength, life, and mechanical tests are used for evaluation by most who participated in the survey. Tests to evaluate materials characteristics such as thermal gravimetric analysis and

potting variable tests are not recognized as standard tests. This implies that many resin customers assume that all the parameters are well defined by the resin manufacturers and need little or no evaluation. Unfortunately, many materials characteristics and processing variabilities are unknown by the material user.

Potting materials tests and storage were limited to:

- Retest of materials stored over 6 months
- Not keeping unused materials in cold storage
- Adhesion tests to metals, tapes, and films with and without primers
- Volume and surface resistivities
- Dielectric constant
- Dielectric strength
- Partial discharges and corona
- Surge tests
- Thermal conductivity
- Thermal gravimetric analysis
- Differential scanning calorimetry
- Dielectrometry
- Pyrolysis gas chromatography
- Gas chromatography-mass spectrometry
- Fourier transform spectroscopy
- Solids analysis
- High-pressure liquid chromatography
- Viscosity
- Coefficient of thermal expansion
- Hardness of cured specimens
- Specific gravity
- Tensile and flexural strength and elongation
- Filler type and content

Potting variable tests conducted during the processing evaluation of materials included:

- Mold and part preheat
- Vacuum .me
- Overpressure
- Overpressure/time

During power supply fabrication the following tests are used by most manfacturers.

- Parts burn-in
- Power supply acceptance test and burn-in
- Accelerated life tests for critical modules
- Temperature cycling
- Mechanical tests

7.2.7 Environment. The lower to upper range of temperature is from -65° to 125°C, depending on the design specification. The higher and lower the temperatures, the more limited the number of available materials to select for the design. The lower temperature is from -40° to -65°C, the airborne requirement at -55°C, and the ground support equipment requirement is at either -40° or -55°C.

7.2.8 Power Supply Voltage. Airborne and ground support power supplies with output voltages below 10,000 volts and less than 2000 W output power are usually potted. For higher power equipment (above 2500 W output), oil or pressurized gas is preferred. As the output voltage is increased to 50 kV or above, pressurized gas and oil-filled modules are preferred for both airborne and ground support equipment. Components and modules such as the control modules and transformers are potted with sufficient space for gas or oil circulation.

7.3 Analysis. Analysis of the government and industry survey dealing with the overall problems associated with high voltage power supply failures shows that some of the same problems exist today that existed '5 to 20 years ago. However, many improvements have been accomplished and today the improved materials are being stressed to much higher values than they were

20 years ago. For instance, 20 years ago electrical stress across an insulation system was between 20 and 50 V/mil. Today, it is commonplace to see electrical stresses from 150 to 350 V/mil for resins where the upper values are used for short life, direct voltage applications. These higher values are achieved through better exchange of ideas between government and industrial organizations in developing lighter weight, smaller volume equipment with longer MTBF and lower life cycle costs. Another area that has contributed to better understanding of materials and their use in manufacturing is the coordination among materials and processing engineers, packaging engineers, and the electrical and mechanical designer with the manufacturing quality control engineers and technical personnel. These findings are constantly stressed at workshops on high voltage technology and in government and industrial reports.

Most responses to the survey stated that high failure rates are associated with:

- Cracks and voids
- Electrical overstress
- Thermal conductivity
- Failure evaluation and repairability

Voids are always associated with resins. The number, size, and location of voids are important. Voids located in equal potential areas or in low electrical stress (less than 20 V/mil for small voids less than 10 mils in diameter) are difficult to find through testing in a high quality insulation system. Voids in higher electrical field stress areas soon tend to be a source of partial discharges and cause deterioration of the insulation system as shown in the example of a film in Figure 70. There the life of polyethylene film is greatly reduced even at very low voltage due to corona and partial discharges over that of void-free material.

Void size and quantity can be greatly reduced by vacuum impregnation followed by overpressure encapsulation. Most manufacturers use vacuum impregnation, many use overpressure. Although vacuum impregnation is good, it must be performed to a precise specification for a length of time and

minimum and maximum pressure; the same for the overpressure. Too much time under vacuum can cause catalyst evaporation, degrading the resin within the insulation system. Therefore, each material must be evaluated for the correct vacuum/overpressure combination to obtain the least number of voids.

Cracks are generally caused by differential expansion and contraction of materials during cure and/or thermal cycling. Evaluation through test is the better method after it is determined that the glass transition point is suitable for the environment to which the component will be exposed. Cracks can also be caused by shock and vibration. Again, testing is the better method.

Electrical overstress is strictly a function for the electrical designer and packaging engineer to determine from material characteristics supplied by the materials engineer. Field stresses can be calculated using textbook formulas. But, the designer must also enter temperature, frequency, and material thickness into his calculations. A source for these calculations is given in Reference 153.

Failure evaluation and repairability can be accomplished best by using either clear or opaque materials. This gives the observer of the failure a chance to visually locate the failed circuit part or component. In addition, soft flexible materials such as silicones and urethanes are easily repaired, whereas the solid epoxies and some hard urethanes must be destroyed or X-rayed to find the failed part or component. Most solid materials cannot be repaired, except as a whole module.

7.4 Problem Areas and Suggested Solutions. High voltage systems are plagued with annoyances that are unnoticed in low voltage systems. Some of the more subtle annoyances are described in the following sections.

7.4.1 Debris. Small dielectric flakes or chips lodged or lying on the surface or edge of a coil will align themselves with the electric field. They will be charged to the same potential as the surface to which they are attached, acting as a point on the surface. This will decrease the utilization factor of the encapsulating gas or oil and cause excessive corona and eventual breakdown.

Inspections and thorough cleaning with high-pressure air will eliminate this problem.

Small pieces of insulation must be cleaned out of transformer cases, otherwise "chips" may lodge in the field between a coil and metal, causing corona, which ruins the gas or oil insulation. Wire terminations should be designed and installed so that the field approaches that of a parallel-plate configuration without point discontinuities. Intermittent partial discharges in fluids cause decomposition into acids and sludges, which degrade the insulating properties of the fluid.

7.4.2 Mechanical Stress. Sharp edges or points on fasteners, connections, and rivets can cause the insulation boards to chip or crack. Terminations should be designed to minimize mechanical stress points on the insulating boards. This can be accomplished by molding the terminal in a solid insulating material that is attached to the board, or by placing metal spacers with flanges through the board. The metal spacers not only reduce the mechanical stress but also increase the surface utilization factor between the flange edges.

7.4.3 Flexible Wiring. Flexible wiring is easily misaligned during the potting process, causing high voltage wires to be overstressed during operation. High voltage, extra-flexible wiring is acceptable in some limited cases, but it should be used only as a last resort. When used, it should be guided from terminal to terminal to eliminate the probability of the wire insulation intermittently touching other surfaces containing higher or lower voltage circuits. Intermittent touching may even cause the wire insulation to puncture and fail. When the wire is in space the insulation outer surface charges to the conductor potential. When it touches or approaches another surface it discharges the stored energy, heats the surface, and degrades the insulation.

7.4.4 Manufacturing Cleanliness. The need for manufacturing cleanliness cannot be overstressed. Clean gloved hands should be mandatory when papers, films, and other cleaned surfaces are handled. Small amounts of oils or acids can cause an improper bond or encapsulation. Any paper, cloth, film, or

other dielectric material is suspect and should be inspected by quality control, shop fabrication, and engineering personnel. Smoke-emitting objects in materials fabrication shops may contaminate the dielectric.

7.4.5 Mold Release Agents. Silicone products may contaminate certain epoxies, urethanes, and other insulating materials. Compatibility and contamination of materials for bonding purposes should be investigated before fabrication. When an incompatibility exists, precautions must be taken to avoid contamination.

7.4.6 Fixture. Mold or potting fixtures should not be used for epoxies or polyurethanes once they have been used for silicone potting. If they are used for both materials, the silicone must be cleansed from all surfaces and joints within the mold or fixture.

7.4.7 Testing. Flaws in outer surfaces and between a single conductor and a surface can be visually inspected. When a coil, circuit, or multiple-conductor assembly is tested, the test must include detection of imperfections between coil layers, circuit parts, and assembly layers. This implies that the total assembly must be energized in such a way that all overstressed electrical parts will be detected. An overvoltage test and/or overfrequency test are two methods for testing.

7.4.8 Environment and Life. Most high voltage circuits and parts are installed in enclosed pressurized containers. This reduces the probability of thermal shock, but not temperature extremes. Testing an insulation in a small dish is inadequate. Fabricated parts and circuits should be assembled (per specification) inside the container and tested through the temperature extremes with all circuits energized. Seven or more cycles are recommended. Pre-environmental and post-environmental tests should include partial discharges, dissipation factor, insulation resistance, dielectric withstanding voltage, and a visual inspection for breaks, tears, and deformation. Any significant changes in appearance or electrical characteristics are reasons for further testing and/or modification before qualification and life testing.

7.4.9 Tabs. Small tabs are often placed on wires and parts for identification and installation. When these coils and circuits are encapsulated, film-tape tabs such as Mylar adhesive may cause built-in gas pockets or voids. These voids may initiate partial discharges and eventual voltage breakdown. If tabs are required, they should be made of porous materials that are compatible with and easily wetted by the encapsulant.

7.4.10 Spacers. Spacers between two energized encapsulated units must be nearly void-free and have smooth or rounded surfaces to reduce tracking susceptibility across the spacer surface. Curved surfaces will reduce the stress across the spacer and the available charging current, but they will not eliminate the problem. The spacer surface should be designed as though the voltage at the dielectric surfaces was from base electrodes, not dielectrics.

7.4.11 Coatings. Coated metal surfaces have higher breakdown voltage characteristics than uncoated surfaces, providing the correct coating material is applied. Some coatings bond poorly, flake, and reduce the electrical stress capability of the two electrodes. Others may have pin holes and voids or blisters that also cause flaking. Coatings must be evaluated under identical environmental and electrical stress conditions to be fully qualified.

7.4.12 Determining Partial Discharge Limitation Voltage. The partial discharge initiation voltage (CIV) of an electrical apparatus can be determined when the design parameters and the applicable Paschen-law curve are known. The Paschen-law curve depends on the type of gas in which the corona would occur, the temperature of the gas, and the configuration of the electrodes. Figure 2 compares Paschen-law curves for different gases. The most common gas is air. If the temperature exceeds 260°C, special Paschen-law curves must be used.

7.5 Designs That Have Worked in High Voltage Equipment. Examples of successful designs used to decrease field stress in high voltage equipment are described in the following sections.

7.5.1 Terminal Boards and Supports. Composite and laminated insulation is used for terminal boards and for supports that separate the coils and wiring from the cores, structure, and containers. A terminal board for high potential should be made from qualified insulation. The board may be flat, if the voltage is less than 20 kV, provided the electrical stress is:

- Less than 20 V/mil for long life (10 to 30 years)
- 20 to 50 V/mil for short life (1 month to 1 year)

For treated and coated boards in a dry, clean atmosphere of pure gas, these values can be doubled.

Terminal boards operating at voltages greater than 20 kV should be contoured to increase the creepage paths. Three basic methods of contouring are discussed in Section 5, Design and Configurations Data.

- Cutting slots (gas-filled regions) between the terminals
- Building barrier strips between the terminals
- Mounting the terminals on insulated standoffs

7.5.2 Wire Preparation and Routing. Low voltage wiring to sensitive circuits should be routed close to the ground plane, avoiding high voltage wiring and circuit elements. High voltage wiring should be kept short and centrally located within potted assemblies. High voltage terminals should be rounded to alleviate high field stresses. Teflon wire and wire routing were major sources of failure of early airborne high voltage power supplies.

7.5.3 Shapes. Rounded shapes should be used on high voltage circuitry for parts when available, terminals, joints, bolt heads, nuts, and screw heads. Where rounded surfaces cannot be used, a semiconducting or metal cap should be placed over the sharp-edged elements. All materials must be compatible with the potting material, have good adhesion, and must not be a source of air bubbles.

7.6 Manufacturing Summary. A listing of the most recurring recommendations are summarized as follows:

- Design power supply to minimize high voltage breakdown and stressing problems; separate high and low voltage areas; designers must educate the technicians
- Be sure that circuit board designs will withstand all high voltage power requirements after encapsulation
- Be certain that maximum heat transfer characteristics are not compromised during fabrication.
- Train personnel associated with the manufacture of high voltage power supplies
- Use highest performance materials, and allow for repairability where mandatory; assure quality control of materials
- Use high performance ruggedizing designs where possible and soft repairable resins where mandatory
- Use low thermal expansion resins
- Use high adhesion resins where possible; control adhesion by tightly controlled assembly cleaning and tightly controlled use of primers
- Use adequate and controlled cleaning processes; prebake all parts to be encapsulated
- Screen critical components; qualify the design
- Control workmanship in critical processes, especially encapsulation and coil winding; give special attention to documentation for materials, processes and controls
- Verify freedom from voids, cracks, contamination and other sources of high voltage breakdown
- Place special emphasis on transformers, since they are usually dedicated devices for each system, whereas many other components are industry standard; also, transformer constructions are highly critical
- Control equipment performance
- Intimate interface between engineering, quality control, test, and manufacturing personnel.

SECTION VIII
TESTS

High voltage insulation is tested to evaluate its physical and electrical properties and to predict its service life. Equipment tests should be designed to verify the quality of the insulation rather than to serve as a failure analysis tool.

8.1 Performance. Performance tests were developed to verify compliance with specified electrical performance criteria. Power supplies are generally tested to meet the environmental levels listed in MIL-E-5400, MIL-STD-454, and MIL-STD-202. Applicable tests are listed in Table 42.

TABLE 42
ENVIRONMENTAL TESTS

Tests	Test procedure
Vibration	MIL-E-5400
Shock	MIL-E-5400
Temperature	MIL-STD-202
Altitude	MIL-E-5406
Humidity	MIL-STD-202
Materials and processes	MIL-STD-454
Electrical performance	Certified Test Specification

Each power supply must be tested to meet the electrical performance requirements. The qualification and specified acceptance units must be tested to meet all the environmental and materials specifications. Materials and process tests are detailed in Section 6, Materials and Processes.

8.2 Insulation Tests. There are two categories of insulation testing: (1) material evaluation and (2) component insulation tests.

Material evaluation tests include tests of the electrical and physical properties. Electrical properties of interest are dielectric strength, dielectric constant, dissipation factor, surface resistivity, volume resistivity, surface resistance, and life at relevant temperatures. Physical properties include flexural strength, tensile strength, bending and twisting ability, water absorption, linear and bulk coefficient of thermal expansion, heat capacity, chemical resistance, and flammability. Materials are evaluated both in commercial testing laboratories and in laboratories operated by insulation manufacturers.

Component evaluation tests that evaluate insulation integrity and life measure (1) insulation resistance, (2) dielectric withstanding voltage (DWV), (3) basic insulation level and pulse (BIL), and (4) partial discharges. Insulation resistance and DWV tests are mandatory. BIL and partial discharge tests are highly desirable.

8.3 Materials Testing. An accepted standard electrical insulation code, that defines nomenclature and test requirements for the high voltage insulating materials would enable the design engineer to establish test hardware quantity, test parameters, and needed test equipment. Suitable code does not exist in a form satisfactory for aircraft work. The best option for the designer is to adapt ASTM, IEEE, and NEMA high voltage testing standards to particular aircraft application.

The following test sequence is necessary to insure high confidence for high voltage testing:

- Visual inspection
- Insulation resistance measurements for volume and surface resistivity
- High potential applied to solid insulation between two metal electrodes
- Tracking tests
- Final insulation resistance measurement
- Life test

When received, electrical insulation should be inspected to confirm dimensions and to locate any flaws, hidden moisture, dirt, or other contaminants. Insulation resistance should be measured, and it should be subjected to a high potential test and the dielectric properties measured.

Present ASTM standard tests do not impose all the operating environment conditions on airborne equipment. Therefore, ASTM tests should be modified by adding tests at pressures comparable to the altitude, environment, and a time-temperature schedule typical of service. ASTM high potential tests for terrestrial equipment are not completely applicable to airborne equipment, but are useful for detecting insulation flaws and incipient failures that will show up as the insulation ages.

Electrical properties of insulating materials should be measured in accordance with the tests methods in Table 43 and in accordance with the pertinent military specification and standards.

8.4 Component and Equipment Tests. The purpose of testing components and equipment is to determine their flightworthiness. The suggested order for these tests is: insulation resistance, partial discharge (PD-1), high potential, (DWV), pulse, and PD-2 partial discharge or corona tests. Partial discharge test instruments are usually referred to as corona test sets.

8.4.1 Insulation Resistance. Insulation resistance is tested by applying a low voltage (50 V to 100 V dc) to the insulation. An instrument sensitive enough to detect picoamperes measures the resulting current, and the insulation resistance is calculated from Ohm's law.

Insulation resistance should be measured before high potential tests to avoid unnecessary failures from defective, damp, or dirty samples. High insulation resistance by itself does not prove that the insulation of a component is free of cracks or other faults where breakdown may subsequently start. Therefore, an insulation resistance test is not a substitute for high potential tests, but should always precede high potential tests.

TABLE 43

TESTS OF ELECTRICAL PROPERTIES OF INSULATION

Tested Property	Test Condition	Evaluated	Test Method
Dielectric Strength	DC/AC 1/4" Electrodes	When received and following environmental stres	ASTM,D-149-61 (Modified)
Tracking	DC/AC	Following environmental stress	ASTM D-495 or ASTM D-2302
Dielectric Constant	1 Kilohertz	When received	ASTM, D-150-59T
Dissipation Factor	1 Kilohertz	When received	ASTM, D-150-59T
Volume Resistivity	125 Volts	When received and following environmental stress	ASTM, D-257-61 (Modified)
Surface Resistivity	DC	When received and following environmental stress	ASTM, D-257-61 (Modified)
Insulation Resistance	DC	Following environmental stress	Based on 0.05 mfd wound parallel-plate capacitor
Life	DC/AC	Vacuum (Plasma)	ASTM, D2304-64T (Modified)

Insulation resistance should also be measured after high potential tests because insulation damage from a high potential breakdown may otherwise be difficult to detect. Lower insulation resistance after a high potential test indicates a failure. Obviously, insulation resistance must be measured for both cases at the same temperature.

The test current during measurement of insulation resistance should be limited to 5 mA. Most "Megger" instruments limit direct current output to 4 mA or less. This limitation avoids unnecessary heating of the insulation at the leakage paths if the insulation resistance is low. Insulation resistance that is low because of moisture can usually be restored by suitable heat treatment.

8.4.2 High Potential Test. In a high potential test or DWV test the intentional grounds of the component being tested are disconnected, and the voltage is applied between mutually insulated elements of the electric equipment and between insulated elements and the frame or "ground." Normally, the test voltage should not appear across solid-state devices. A common test voltage for 28-volt and 120-volt equipment is two times normal plus 1000 volts. Airborne electronic equipment is tested with lower voltage, especially if short-life and dense-packaging is involved. Sometimes this equipment is designed with a DWV of 16 percent of the operating voltage. The DWV should be at least 160 percent for quality hardware.

High potential tests are designed to electrically stress high voltage components and equipment, but with safety margins sufficient to protect the equipment from damage or malfunction. The basic damage or malfunction mechanism for components and equipment relates to the DWV. Parts with similar or identical electrical insulation should have similar or identical DWV if care has been taken to ensure good quality control.

High potential tests are intended to detect insulation flaws, discontinuities, aging cracks, and deteriorated or inferior insulation. A hole or crack in insulation, through which an inductive surge voltage will discharge and ultimately "carbonize a conductive path, may be detected by a

high-potential test if the test voltage is adequate to induce failure. Test voltages under 750 volts rms are too low to ensure that flaws will result in breakdown.

The high potential should be applied for 60 second. Repeated application of high potential test voltages can reduce the dielectric strength and life of insulation. Any significant reduction in dielectric strength depends on the number of tests, the insulation material, and the insulation thickness. Up to ten high-potential tests would probably not permanently damage the insulation. CAUTION: The first DWV test should be at the full DWV rated voltage. Successive tests should be derated and not exceed 80 percent of the original DWV test voltage. This procedure will prevent unnecessary insulation damage.

Some systems have large voltage-transients generated by rectifiers or mechanical switches. The DWV test must exceed the highest of these transients by at least 20 percent. Each application must be assessed on the basis of required operating life and operating conditions.

8.4.3 Pulse Tests. Pulse or basic insulation level (BIL) tests are required for components and equipment which will be used where electromagnetic pulses (EMP) or switching surges are expected. A BIL test subjects the insulation to a voltage pulse having a risetime of about 1 μs.

A high voltage public utility apparatus is specified to meet lightning and transient insulation standards, in addition to the dielectric withstanding voltage requirements. These transient requirements are referred to as the BIL for the insulation system. The BIL is based on a pulse with slower rise and longer duration than an EMP. Thus, using the BIL is a conservative approach to designing electrical insulation for fast EMP transients as long as the amplitude is comparable. The slowest EMP transients are essentially the same as the BIL standard transient.

Basic insulation levels were defined during the joint January 1941 meeting of AIEE-EEI and NEMA Committees. This group adopted the basic

insulation levels in terms of pulse duration voltage amplitude according to the following definition:

"Basic impulse insulation levels are reference levels expressed as impulse crest voltage with a standard wave no longer than 1.2x50 μ s (1.2 μ s rise to 0.90 peak voltage and 50 μ s decay to 0.5 peak voltage) (Figure 93). Apparatus insulation as demonstrated by suitable tests shall have capability to, or greater than, the basic insulation level."

This definition requires that equipment and components conforming to the definition have a pulse test value not less than the kilovolt magnitude entitled BIL. Also, equipment and components conforming to these requirements, with a few exceptions for solid-state devices, should be capable of withstanding the specified voltage, whether the pulse is positive or negative in polarity. Standard atmospheric conditions are assumed.

The joint IEEE-EEI and NEMA committees have agreed upon BIL values for high voltage transmission and distribution equipment and components to ensure continuous system operation during and following lightning and transient conditions. The committee has not standardized BIL values for all low voltage and airborne electrical equipments; that is, equipment and components with operating voltages less than 1200 volts rms (1700 volts crest) or equipment and components operating at altitudes above 10,000 feet.

Insulation is able to withstand higher voltages, within limits, as the test duration becomes shorter (Figure 94). Experiments have shown that insulation will function for 20 to 50 years if its initial 1-minute DWV is two times the operating voltage plus 1000 volts. Experiments have also shown that the electrical insulation breakdown voltage could be increased 20 percent if the DWV time was decreased from . minute to 1 to 5 seconds.

Most experimental work has been with either 50 to 60 Hz ac or steady-state dc. Power industry tests show the steady-state dc voltage a given insulation can withstand is higher than the crest value of the ac voltage it can withstand. When a dc voltage is applied, the dielectric is charged only once.

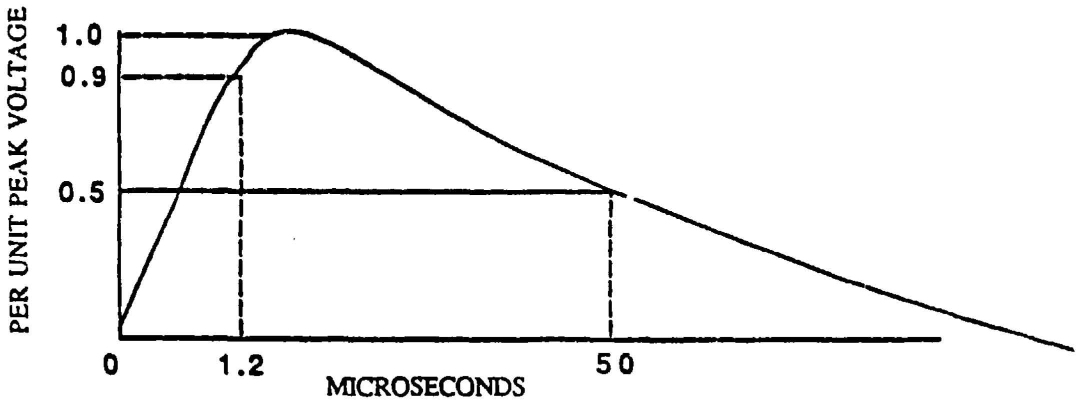

Figure 93. Waveform for Basic Insulation Level (BIL) Definition

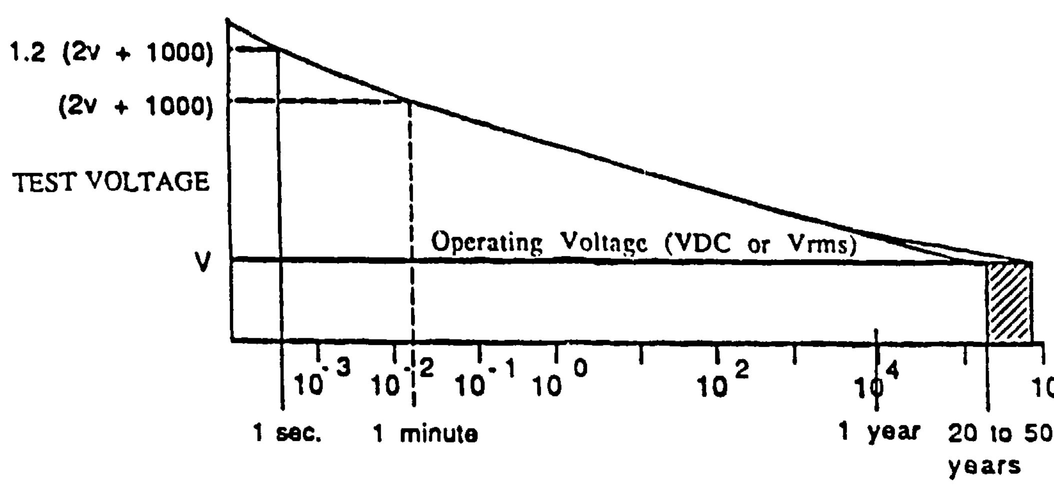

Figure 94. Dielectric-Withstanding-Voltage Margin Affects Insulation Life

On the other hand, the cyclic charging and discharging with ac voltage applied heats the dielectric because of internal friction. When steady-state dc voltage is applied, the only heating of the dielectric is from current flow through the insulation resistance. Early experiments with insulation showed the dc rating of insulation to be:

$$\text{Rating in volts dc} = \left(1.7 \text{ to } 2\sqrt{2}\right) \quad \text{(ac rating in volts rms)}$$

Factors that decrease the pulse level an insulation can withstand are material aging, power system transients experienced, and the maintenance status of the equipment. These phenomena decrease insulation pulse ratings to the range of 0.75 to 0.85 of their original values.

An insulating material is also degraded by repeated pulses. This degradation is time variant (Figure 95), with less than 10 pulses having little effect on the insulation integrity. The data in Figure 95 imply that the breakdown of insulation proceeds with the growth of prebreakdown channels created by previous pulsing. The process has three distinct phases: (1) an initial period during which the pulses initiate a prebreakdown channel, (2) a slow growth of the channel, and (3) a fast growth of the channel. For example, over 10,000 pulses were required for the slow growth of the channel in epoxy insulation for a pin-to-plane configuration, with the pin spaced 5 mm from the plane (Reference 159).

Experiments by Rzad, et. al. (Reference 160) with a rounded rod of various gap lengths in transformer oil are shown in Figure 96 for 100- μ s square wave pulses. Increasing the voltage using the 100- μ s pulse shortens the time to breakdown for a given gap length. For a square wave pulse it was also shown that the breakdown voltage was essentially the same for both polarities. The breakdown in oil becomes linear with gap length versus time for larger gaps.

Another group of experiments was made by Katahoire, et. al. (Reference 53) studying the breakdown along a cross-linked polyethylene (XLPE) sample submerged in silicone oil (PDMS), using a standard 1.5/50 μ s pulse. The pulse

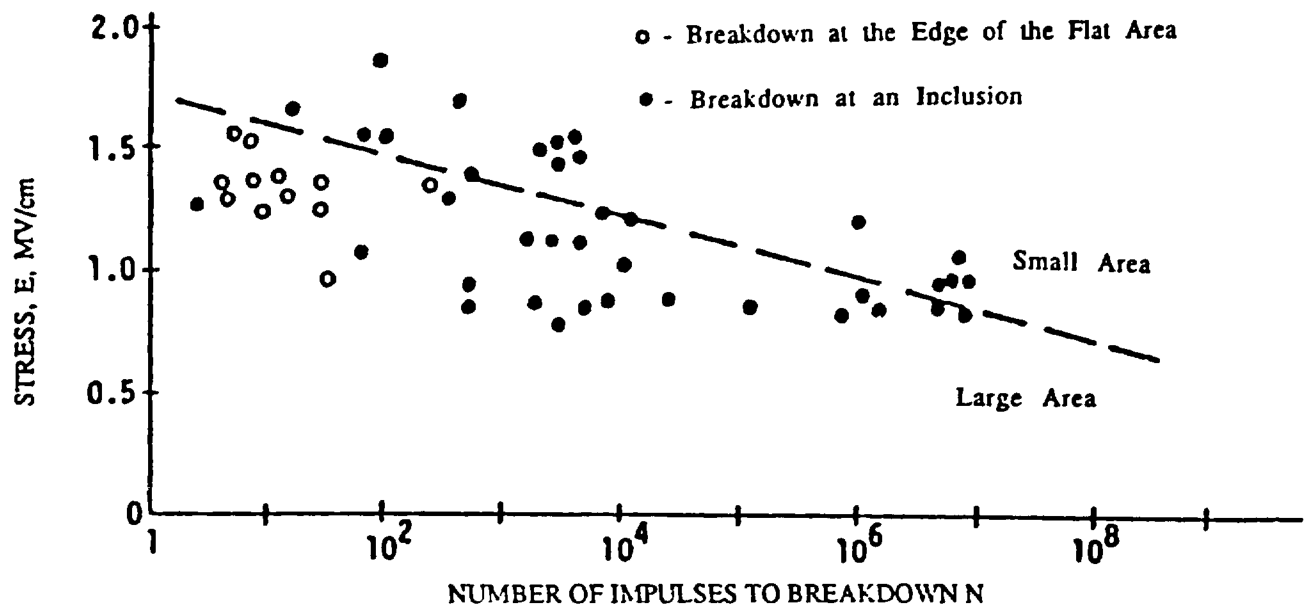

Figure 95. Relation Between Electrical Stress and Number of Impulses Required to Produce Breakdown with 1/50 Microsecond Impulses

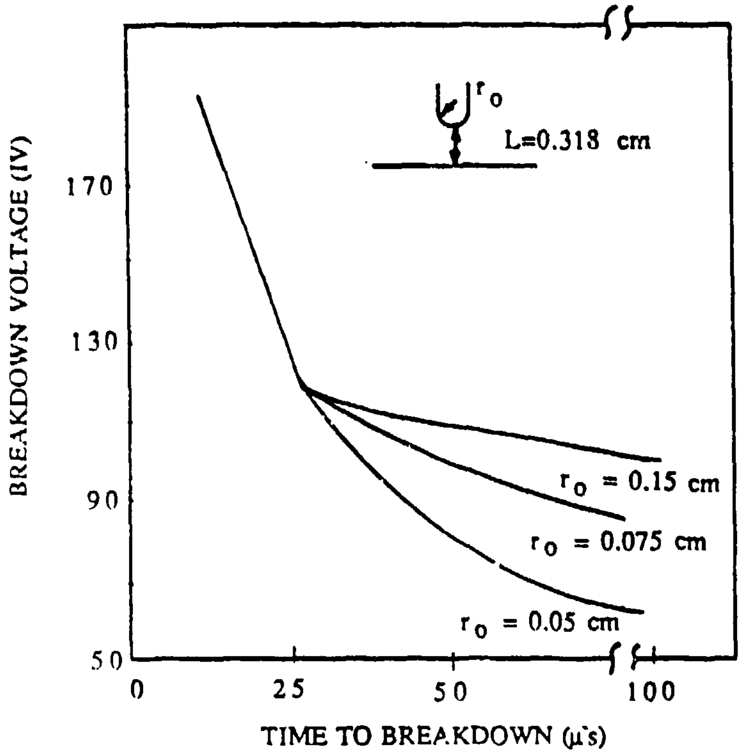

Figure 96. Time to Breakdown Vs. Breakdown Voltage In Transformer Oil for 100 Microsecond Rectangular Voltage Pulses Between Rod-Plane Electrodes

voltage is compared to the breakdown at power frequency (60 Hz) for the same electrode configuration in Figures 17 and 97.

Pulse voltages for public utilities are much too high for airborne equipment, where compact packaging requires small bushings and minimum dielectric thicknesses. Although airborne equipment is not normally designed to withstand lightning-induced transients, its pulse test voltages should still be twice the rated voltage.

Pulse tests, like dielectric withstanding voltage tests, can be destructive and must be carefully planned and executed. Some rules of application for pulse and dielectric withstanding voltage tests are as follows:

a. Pulse tests peak voltage should not exceed 200 percent rated (peak) voltage.
b. Pulse and DWV tests should be limited to incoming inspection, component acceptance, and system or subsystem acceptance. Overtesting overstresses the dielectrics and some critical electric parts.
c. Tests beyond the group outlined in (b) should be at the reduced value of 80 percent to 85 percent of the original value.
d. The DWV and pulse tests must be magnitude-limited tests. That is, the magnitude must be limited to coincide with the dielectric stress within the test article insulation system. For instance, capacitors in pulse-forming networks are already rated near the electrical stress limit of the insulation system.

Components and equipment recommended for pulse tests are cable assemblies, capacitors, and inductors used in high voltage, high-power equipment. Pulse tests are not recommended for delicate experiments or very low power equipment.

8.4.4 Partial Discharge and Corona Tests. Partial discharge and corona tests are used to seek out insulating material flaws by detecting partial discharges. The most common insulation imperfections in equipment are entrapped gas in

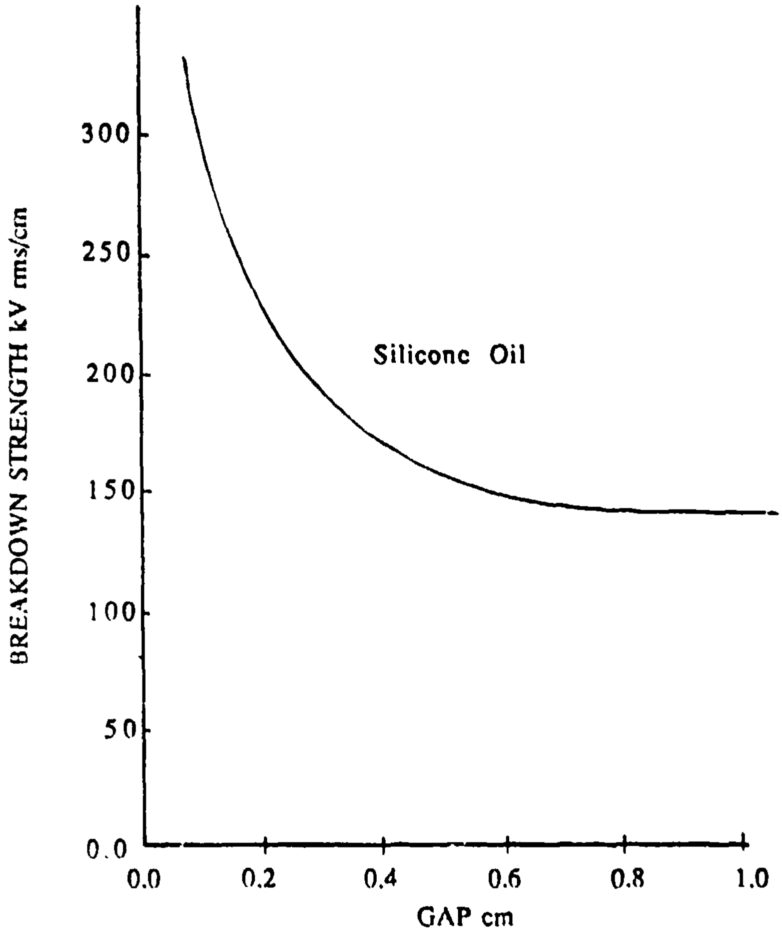

Figure 97. Power Frequency Breakdown Strength of Silicone Oil Between Cup-Plane Electrodes

voids and cracks within insulation, and insufficient space between an insulated conductor and ground or other insulated parts. As examples of defects, a transformer coil may have small voids within the insulation, between the active conductors and the magnetic core, or between the turns of two coils.

8.4.4.1 Detector Types. Corona is the flow of electrons in a gas surrounding a high voltage element. By contrast, a partial discharge is a flow of electrons and ions that occurs in the gas in a small flair in the total insulation system. This short-duration event emits acoustic, optical, and radio frequency energy. Partial discharges can be detected by measuring any of these radiations (Reference 160). Although the direct-coupled measurement of the radio frequency current and voltage pulses is by far the most widely employed by industrial organizations, other forms of detection do exist. These discharges can be photographed or observed with photomultipliers. Acoustic signals can be measured at several locations by triangulation, used to localize the discharge.

Detectors placed near test articles should not distort the operating characteristics of the test articles or the test equipment. Detectors for use near high voltage equipment must be sufficiently sensitive so that they can be located away from the critical parts of the high voltage field.

Optical sensors must have sensitivities compatible with the low line emission typical of corona and partial discharges. Visible corona can be detected on exposed test parts if the test can be operated in total darkness. With enclosed equipment, the optical detector must be located within the package.

In tests where a solar simulator is used to illuminate the test article, optical corona detection is difficult, if not impossible. Even with adequate shielding, detection may be difficult except where the detector can be directed toward the part in which the visible corona is expected.

Gaseous (ozone) detectors are required to have sensitivities sufficient to detect ozone in the test environments. Because the environment must contain

oxygen, this limits their usefulness at high altitudes. Again, at its spacing from the test article the detector must be sensitive enough to detect the ozone. Requirements of electrostatic detection systems are that they be sufficiently sensitive to be placed a convenient distance from the test article and that the circuitry and readout equipment be capable of distinguishing the corona, a partial discharge, and signal from background noise. The long lead to the readout equipment makes this a difficult requirement to fulfill.

Detector concepts that are capable of detecting corona and partial discharges are described in Table 44; however, no single detector can measure all of the phenomena.

Capacitance-coupled detectors are recommended for attachment to specific circuits. These detectors have excellent response, and are easily installed. The radio frequency coupling loop is recommended because it can be moved about to pick up extraneous generated noise. For very large equipment, an antenna or electrometer is recommended. These detectors are lightweight, easily mounted, and insensitive to light and heat.

Coupling loops and direct-coupled capacitors are used in many test circuits. These devices are small, easily installed, and, in the case of the coupling loop, can be moved from place to place on the test article. A direct-coupled capacitor is typically used in a simple circuit such as a voltage multiplier in a voltage divider. The capacitor can be connected to one of the low voltage devices, and the signal fed into a detection circuit. For more complex circuits such as power supplies, electronic circuits, large pulse modulators, or scientific experiments, a radio frequency coupling or direct coupled capacitor is recommended.

Not enough is known about partial discharges and their effect on materials for their measurement to be the only criterion for insulation life assessment for a given applied voltage. Other tools such as high potential testing, dielectric stress calculation, and life testing are required for a full assessment.

TABLE 44

CORONA DETECTION CATEGORIES

CATEGORY	TYPES	APPLICATION	COMMENTS
Light Sources	• Solar cells • Photomultiplier • Cameras • Television Cameras • Solid-State Detectors	• Measures light generated by the gaseous ionization between the open electrodes in a darkened chamber.	• Sensitive to stray light • Mobile • Cannot measure discharge in voids or enclosures. • Very Directional
Mechanical	• Accelerometer • Ultrasonic	• Measures mechanical vibration set up by gas pressure shock waves.	• Massive discharges are required • Subject to external noise sources • Light insensitive
Electromagnetic Radiation	• Voltage Standing Wave Ratio • Antennas • Electrometer • Sato Probe • Capacitor Probe	• Measures radio frequency emmanations generated by the gaeous discharge.	• Light, temperature and pressure insensitive • Mobile • Sensitive to outside radio frequency impulses • Semi directional • Unattached to the test article
Electronic Pickups	• Capacitor Coupling • Attached RF Coils • Series Resistors	• Measures the high frequency voltage and current impulses generated by the corona partial discharges.	• Attached to the corona sensitive circuit • Immobile • Light, temperature and pressure insensitive
Chemical Detectors	• Mass Spectrometer	• Measures generated ozone and outgassing products.	• Must be located close to the discharg • High voltage power supply required • Non-directional
Scientific Instruments	• Geiger Counter • Curved Plate Analyzer • Cerenkov Detector • Solid-State Detectors	• Measures charged particles radiated by the corona discharge.	• Located near the discharge • Mobile • High Cost • Requires special modification and instrumentation.

8.4.4.2 Corona Test Sets. Partial discharge or corona test sets are designed with electronic detectors. Both the partial-discharge initiation voltage and the extinction voltage are usually measured. The waveform of the partial-discharge pulse is observed to determine the magnitude and type of discharge. The variation in the number and sequence of pulse heights as a function of voltage and time can be measured, and the pulse energy can be derived from the voltage waveform. From such observations, important insulation characteristics are established, including maximum acceptable operating voltage, quality of insulating materials, quality of insulation design, insulating materials life potential, and type and size of voids and cracks.

Partial discharge detectors are designed and calibrated for commercial testing of high voltage transmission lines, electrical machinery, and for testing small samples of dielectric gases and materials. During test, these detectors are directly or indirectly coupled to the test article. These directly coupled detectors, unless modified, are unsuitable for vacuum testing.

The output of the detector must be processed to extract the partial-discharge signature from the noise. A refined bridge circuit that nulls out transients generated in the power supply is shown in Figure 98. For precise measurements a pulse-height analyzer is used with detection circuits to permanently record test data and evaluate degradation of materials (Figure 99).

The input impedance to the detector is usually determined by an rf tuned circuit having a large impedance to a certain frequency band in the partial discharge spectrum. The detected signal is amplified and displayed on an oscilloscope screen or recorded electronically. Most commercial detection systems use one of two forms of detection circuitry. The narrow-band impedance has a bandwidth of about 10 kHz, centered between 20 and 30 kHz. The wide-band detection has a bandwidth of about 100 kHz with a center frequency between 200 and 300 kHz. In both cases, the output of the pulse amplifier is relatively easy to observe, even on older models of cathode ray tubes. The pulse output is usually displayed with respect to the power frequency voltage to aid discrimination between PD and electrical noise.

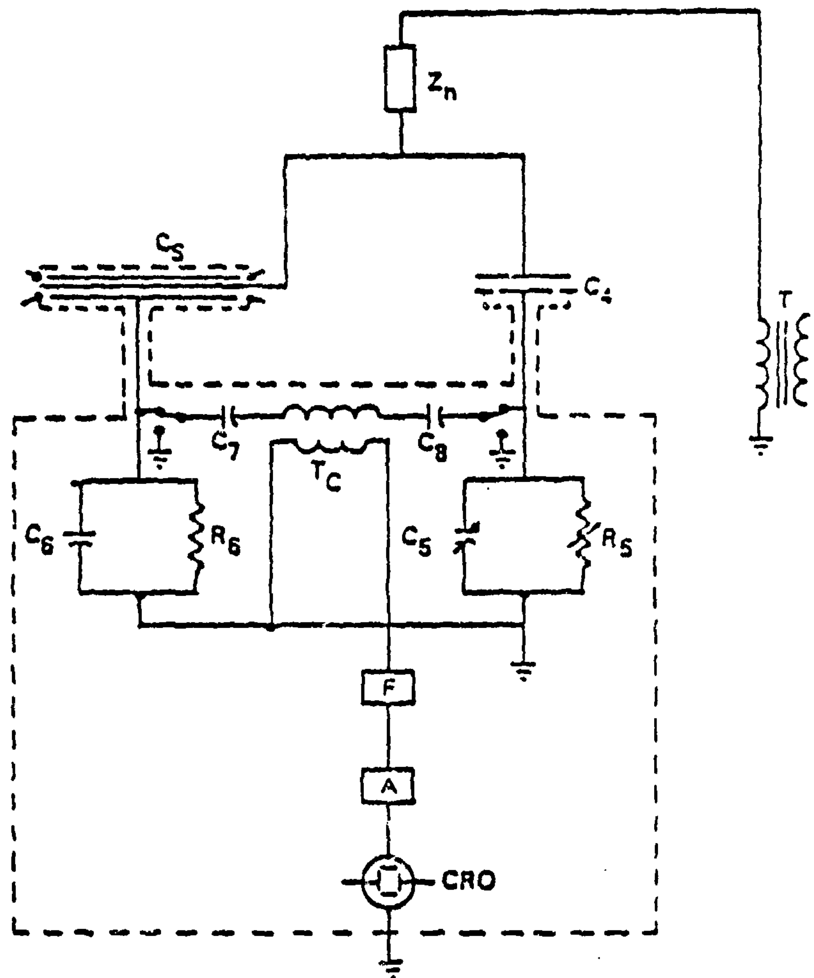

Figure 98. Bridge Detector Circuit

T	-	High Voltage Transformer
Z_h	-	Separating Impedance (Minimum Inductance 0.1 H)
C_s	-	Capacitance of Test Article (1000 to 4000 pF)
C_4	-	Coupling Capacitance (1,500 to 3,000 pF)
C_5	-	Variable Low Voltage Capacitance (0 to 10,000 pF)
C_6	-	Low Voltage Capacitance (1,000 to 3,000 pF)
C_7,C_8	-	Filtering Capacitance (1,000 pF)
R_5	-	Variable Resistance (0 to 100,000 Ohms)
R_6	-	Resistance (200 to 1,000 Ohms)
T_c	-	Coupling Transformer (Inductance of Which is Chosen so to Obtain Oscillation Frequency 15 to 30 kC/s)
F	-	Band Pass Filter (Pass Band 10 to 50 kHz)
A	-	Amplifier
CRO	-	Oscilloscope

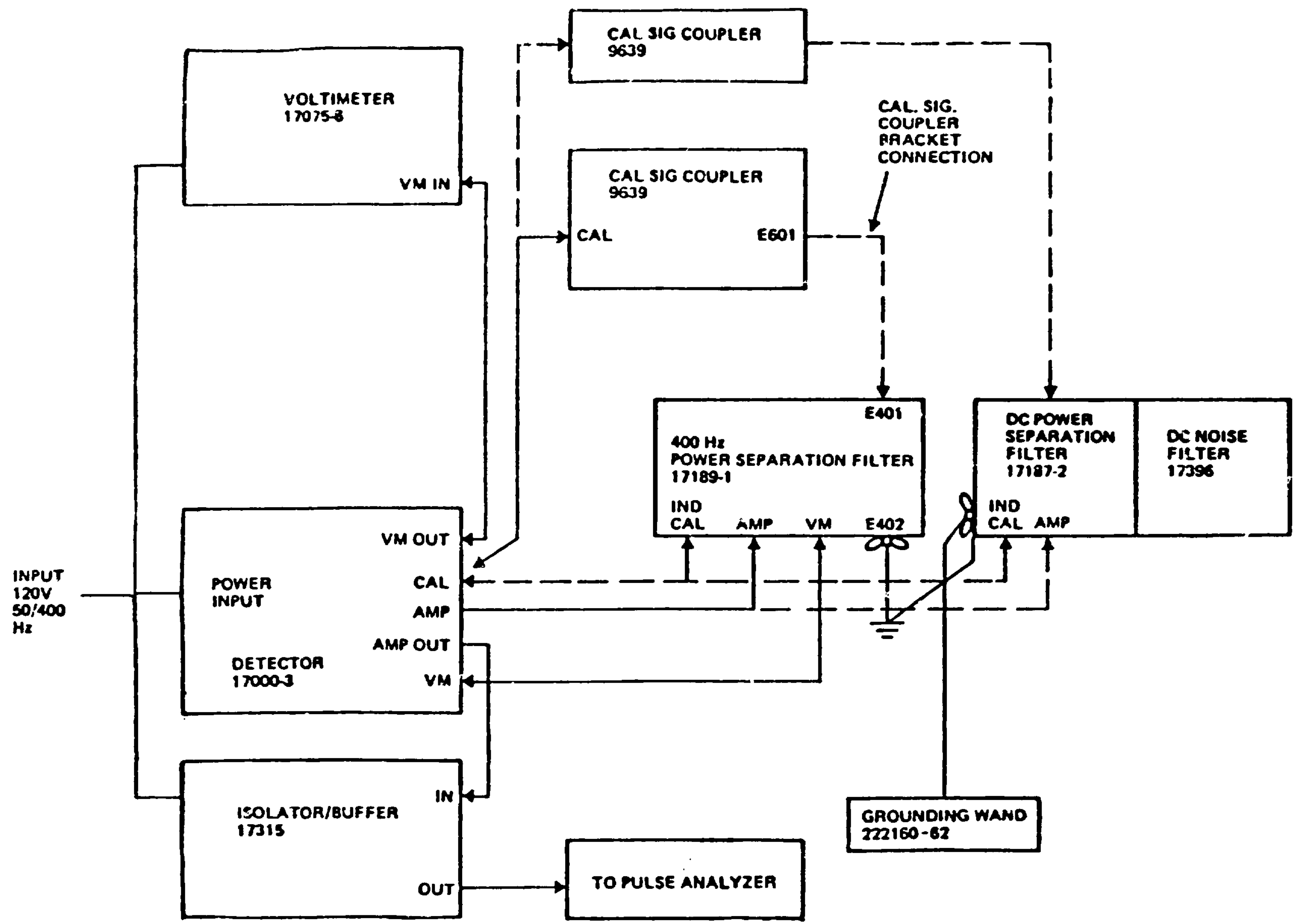

Figure 99. Corona Test System Schematic

Recently, ultra-wide bandwidth (1 GHz) amplifiers and real-time oscilloscopes have been developed that permit the direct observation of low repetition rate pulses of 1 ns or less duration (Reference 161). Therefore, with properly designed ultra-wide bandwidth coupling systems (100 kHz to 1 GHz) detection of partial discharges is possible. These ultra-wide bandwidth detection systems are schematically the same as the system shown in Figure 99, except the separation filter and detection impedance Z must be implemented as part of a transmission line to obtain good frequency response.

The advantage of the ultra-wide bandwidth detection system is that a more accurate observation of the true shape of a partial discharge current pulse, rather than the integral of this pulse (the charge) can be observed. In addition, with the use of two or more coupling capacitors on a test article, the sites of partial discharges can be located to within a small area by measuring the times of arrival of pulses at each coupler. Last, the ultra-wide bandwidth system facilitates discrimination between partial discharges and electrical noise (Reference 162), without isolating the ground of the equipment under test. For some configurations, substantially higher sensitivity is possible.

8.4.4.3 Frequency, Waveform, and Interference. Assessing the effects of frequency and waveform requires careful instrumentation. Most commercial detectors, as recommended by the ASTM D9.12.12, Section L, Committee on Corona, are designed to operate with either dc or sinusoidal ac, with 50 and 60 Hz ac frequencies preferred. Most investigators working with corona and partial discharges have tested, when possible, with 50 or 60 Hz, and extrapolated the resulting data to 400 Hz. When testing dc-to-dc converters with frequencies from 1000 Hz to 50 kHz, detection equipment must be modified to accommodate these frequencies.

With square waves, the detector picks up the leading and trailing fronts of each wave and displays them as very large pulses that look like partial discharges having hundreds of picocoulombs of charge. These pulses, of course, must be separated from true partial discharge pulses in the subsequent processing. An oscilloscope, if used, must be kept from becoming overdriven. The detected signal from the bridge is normally amplified by a high frequency

amplifier and displayed on the oscilloscope. Appropriate phasing of the oscilloscope trigger signal with the power frequency, or Z-axis modulation, can be used to blank out the leading edge from the oscilloscope display, thereby eliminating input saturation due to leading and trailing edge signals.

Signals with a charge of less than one picocoulomb should be measured in a well-shielded screen room. High frequency partial discharge signals of less than 1 μV amplitude are easily lost when the background includes interfering signals of several microvolts. The power supply should also be appropriately isolated.

Several articles written on gaseous breakdown indicate that the Paschen-law minimum is affected by frequency, as established in Section 3. Section 5 showed that the failure time of an epoxy varies inversely approximately with the applied voltage frequency (Reference 163). With these data it can be readily established that the partial discharge and life testing of high frequency components at 60 Hz give poor or inconclusive results. Unfortunately, corona test equipment for partial discharge testing is designed to operate at 25-Hz to 2-kHz frequencies, much lower than the aerospace power electronic equipment frequencies of 10 kHz to 1 MHz. Recently, Dr. Eeman developed partial discharge detection apparatus for spacecraft operating at the lower power electronic frequencies (Reference 164). The output from that equipment is similar to that obtained by tests several years ago by the author (Reference 164). In those tests, it was established that the partial discharge initiation voltage is somewhat frequency dependent. Now a movement should be made to develop high frequency partial discharge test equipment and techniques for testing high frequency commercial and aerospace high voltage power electronic equipment. The new test procedure should also establish partial discharge limits. Most test methods only say "test." Anyone can "test", but the problem is how to interpret the test. Test limits must be established (References 165 and 166).

8.4.4.4 <u>Calibration and Partial Discharge Comparison</u>. Partial discharges at high altitude (30 torr) have frequency spectrum components up to 100 MHz (Figure 100) (Reference 167). The transit time for an avalanche discharge is

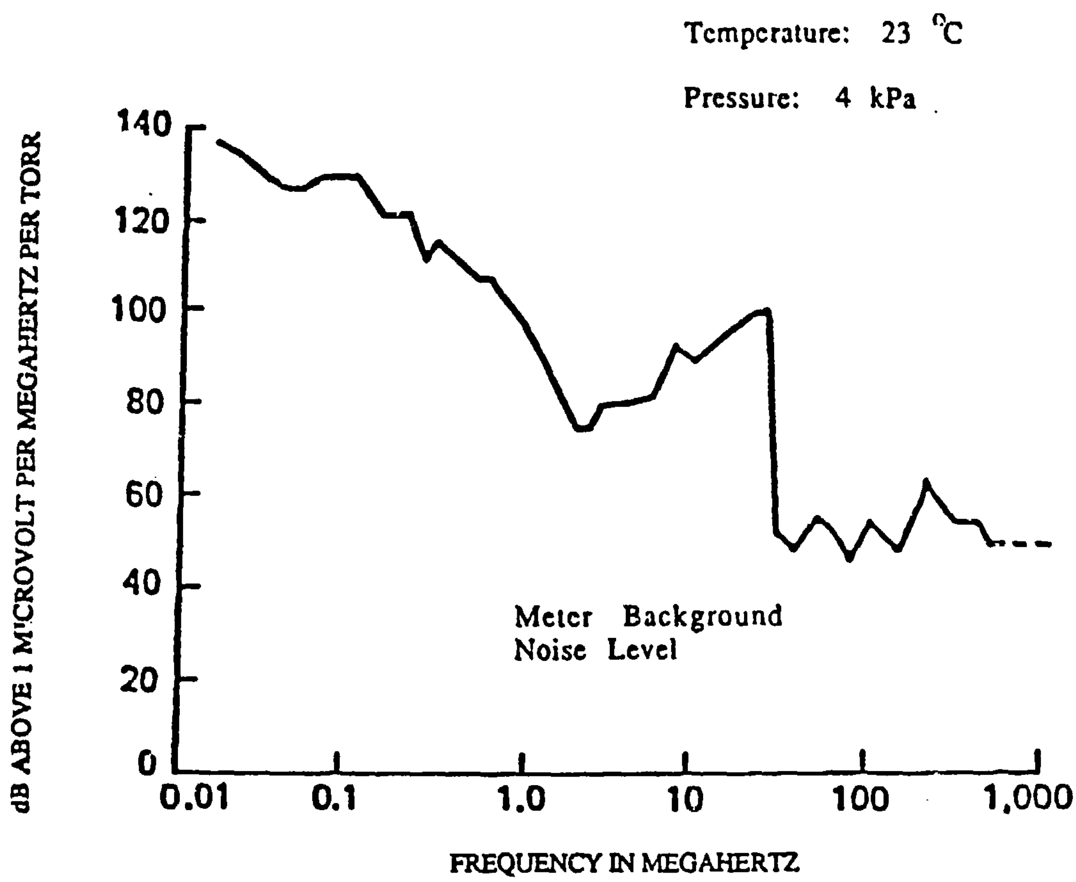

Figure 100. Frequency Spectrum at Corona Discharge

between 0.3 and 20 ns, depending on the voltage, gas, and spacing. This indicates that calibrating with a slow pulse of a few microseconds would not be representative of a partial discharge. For example, in measuring partial discharges within 5 μF capacitors, calibration with pulse risetimes of 5×10^{-7} seconds produced good correlation with the capacitor partial discharges. When longer risetime calibrating pulses were used, the calibrating pulse correlated poorly with the partial discharge pulse height.

8.4.4.5 Special Tests. When evaluating aerospace equipment, it is not sufficient to merely measure the height of the biggest particle discharge (pC) pulse, it is more important to measure the total quantity pulses and their pulse height distribution as reported by Burnham (Reference 168). Dr. Burnham's report shows the test data and analyses for several capacitors using a thermally stimulated discharge (TSD) test. This test excites partial discharges in the test sample by applying a very high stress to the dielectric under conditions that allow the charge to be stored on the dielectric surface and then to be integrated by measuring the thermally stimulated current by a TSD test. These tests and analyses show that the degradation mechanism is damaged by electrons accelerated in small voids, which give rise to low-level partial discharges. The cumulative effect over a long time leads to dielectric failure. This analysis could be established for parts and components other than capacitors if the level of partial discharges can be quantitatively measured during a life test, and the actual electric field distribution in the dielectric is known.

8.4.4.6 Test Criteria. Since 1975, more emphasis has been placed on partial discharge tests than any other test. Some simple rules to follow for partial discharge tests are:

- All high voltage parts and components should be partial discharge tested.
- Partial discharge magnitudes should be recorded using a pulse height analyzer.
- Go/no-go testing must be carefully planned.

- Overvoltage partial discharge testing is life degrading and must be limited in total time for each component within the system.
- Each test must be well planned for each type of part and component. The test operator must be skilled and in direct contact with the high voltage engineer to discuss all abnormalities; failures; and acceptable parts, components, and systems.

8.5 Performance Testing. Destructive and nondestructive tests are used for the qualitative evaluation of electrical and electronic parts and insulation. In the following test, the expression "parts" refers to electrical resistors, capacitors, coils, and solid-state devices.

8.5.1 Testing and Detection. Generally, the test philosophy for electronic parts and hardware should be that sample flight parts, as well as engineering, development, prototype, and qualification equipment, should be thoroughly and extensively tested and stressed repeatedly to establish the margin of the design. Equipment intended for qualification should first be tested to acceptance levels to verify workmanship and to identify early failure causes. Flight equipment should never be subjected to repeated electrical tests. One test of qualified flight equipment should be sufficient to verify workmanship and expose early failure conditions. On the other hand, cumulative electrical stress jeopardize its operating life.

8.5.2 High Voltage Testing. Ac high voltage testing is normally conducted to establish voltage endurance as a function of time. Ac testing is usually a go/no-go type, with voltage being raised to a specified value with samples that break down within a specified time being rejected.

Dc high voltage testing procedures usually differ from ac procedures because leakage current is measured as the voltage is raised. Current that varies linearly with the voltage indicates the equipment is in good condition. As the breakdown point is approached, the leakage current increases at a higher rate, followed by an avalanche current. With some newer insulations,

this knee in the current plot is almost a right-angle bend. The rate of application of voltage rise also affects the breakdown point.

Reproducible measurements are hard to achieve in very high-temperature, high voltage testing because insulators that support the equipment and wiring must be cooled to keep them from becoming partial conducting. This creates temperature gradients in the chambers, and even though the gas in the chamber is at constant pressure, its density will vary inversely with its temperature. The partial discharge initiation voltage is affected by gas density, so ambiguities are introduced into the susceptibility of the different parts of the high voltage circuit. Careful design of the test, complete temperature instrumentation, and detailed analysis of test results is required to obtaining valid test results.

8.5.3 Parts Tests. A part that is to be evaluated for partial discharges should be completely insulated and placed within the configuration in which it will be in the modular aircraft. Pretest processing should include cleaning and potting of parts, and the cleaning and solder-balling of the terminations. For example, if the part is normally on a conformally coated circuit board, then the test article should be assembled in the same way. The spacing between the part and the ground plane should be the same as it will be in the final application. This includes all upper, lower, and side ground planes, which will limit the field gradients and establish the pressure-spacing dimensions for partial discharges.

The altitude chamber feedthroughs and connections must be free of sharp corners and edges to prevent corona from the high voltage gradients present at such points. No gas pockets or outgassing materials should be associated with the chamber feedthroughs or connections to the part being tested.

These outgassing parts can create localized zones of higher pressure near the test article, and raise corona initiation voltage for pressure greater than 100 Pa. The test fixture used is one of the most important parts of the test, and must be in its exact position during test installation. All connections and

interconnections must be solid, free of outgassing, and corona-free. The best partial discharge detector for testing parts, insulated electrodes, and the gaseous breakdown between fixed electrodes is the bridge corona detector circuit shown in Figure 98. This detector is simple, easily connected, and accurate; however, it has limited sample capacitance range. This is determined by the high voltage coupling capacitor and resonant circuit limitation.

8.5.3.1 Dc Ramp Test. Partial discharge data has been taken by R. S. Bever using the dc ramp method (Reference 169) to detect the internal flaws in ceramic capacitors. More recent results were correlated with the scanning electron microscope (SEM) photographs. Results of these tests must be interpreted to determine (1) if partial discharges are above a certain level, do the capacitors have cracks and/or delaminations as well as porosity, and (2) if the partial discharges are similar for all capacitors and the SEM photographs are consistent, is the ceramic material only porous or are cracks present? This test method has proved successful for evaluating ceramic capacitors for voltage multipliers and other dc applications. Capacitors should be given insulation resistance, capacitance and dielectric withstanding voltage tests before the dc ramp test. As for other partial discharge tests, the leads should be kept shorted before and between tests.

8.5.3.2 Accumulative Charge. It has been established through extensive life testing on low voltage capacitors that capacitor life varies inversely to the power law, as expressed by:

$$L = kV^n$$

where L is the life in hours and k is a constant. V is the applied voltage, and n is the power. For low voltage capacitors n has been found to vary from 4 to 12. J. Burnham (Reference 168) found that n varies from 6.8 to 8 for metallized Mylar and polyethylene film capacitors. In the experiments he found that it is not sufficient to measure the height of the biggest pulses, as is done in most partial discharge measurements for components. The total cumulative charges must be measured to establish capacitor life. In a particular test Burnham found that sufficient damage to shorten life occurred at approximately

$2.0 \times 10^7 p/cm^2$ accumulated charge. Accumulated charge was measured using pulse height analyzers.

8.5.3.3 Wire Test. Several types of insulated conductor or wire tests can be performed: insulated conductor to mandrel, parallel conductors, and coaxial conductors. Each type test has rules that must be followed before test. To measure corona in shielded cables, the outer surface of the cable insulation should be painted with a conducting material before attaching the detector to eliminate insulation to shield partial discharges.

a. Parallel Pair. Spaced parallel conductors require the base on insulated ends be sealed or potted to properly space the conductors. For best results it is much easier to have wire "A" go to ground from one end of the pair, and wire "B" to high voltage on the other end of the pair. Connecting ends should extend beyond the potted sections where the non-connected ends are terminated.

b. Twisted Pair. A twisted pair should be treated as the space conductors. If the ends are allowed to flair without potting, or if the potted section is too short, partial discharges or corona will exist and fault the test.

c. Single Wire to Mandrel. Partial discharges can exist in two locations; between the center conductor and the insulation, and between the insulation and mandrel. If the application involves a test of an insulated wire to a ground plane, no special conditioning need be applied. If the application is to determine the capability of the wire insulation, then the wire section that lies on the mandrel surface should be painted with a thin coat of conducting material, such as an aluminum paint. This will prevent partial discharges from forming between the mandrel and insulation outer surface.

8.5.4 Circuit Tests. Circuits consisting of simple assemblies of parts can be tested in the same way as individual parts. More complex circuits require special tests or additional detectors. An example of a simple circuit is a voltage divider network or a voltage multiplier. A more complex circuit would be a power supply, a filter circuit, or the high-voltage electronic system.

8.5.5 System Tests. A high voltage circuit within an electrical/electronic system is difficult to test and analyze unless the individual high voltage circuits are instrumented as just described. Often detection devices must be placed as near as possible to the high voltage elements. Applicable detectors for this purpose are RF coils, capacitors, antennas, and ultrasonic detectors.

A typical test circuit and a high-voltage power supply circuit to be tested for corona are shown in Figure 101. The high-pass filter rejects frequencies less than the fifth harmonic of the power supply transformer frequency, thus eliminating much of the noise from the switching devices. However, there will still be noise on the oscilloscope caused by the switching devices and resonant circuits within the test circuit.

Another essential part of the test circuit is the calibration circuit, shown in Figure 102. A second coupling loop is used for this circuit. The calibration loop is placed about 2 inches in from the sensor loop. Usually a 10 pf capacitor is used for calibration. The square wave signals can be varied from 10 mV to 10 V and the oscilloscope output pulse heights recorded for calibration. This type of sensor must be calibrated before testing commences. The sensor loops are then placed near or on the surface of the test article, as shown in Figure 103, and the electronic circuit is tested.

8.6 Facility and Environment. High voltage airborne systems must often be tested in a temperature-controlled vacuum chamber, which of course must be designed to be corona-free. Corona sources that have been encountered in environmental test chambers include:

a. Pressure gauges
b. Heater panels
c. Light sources
d. Wiring, cabling, and connectors

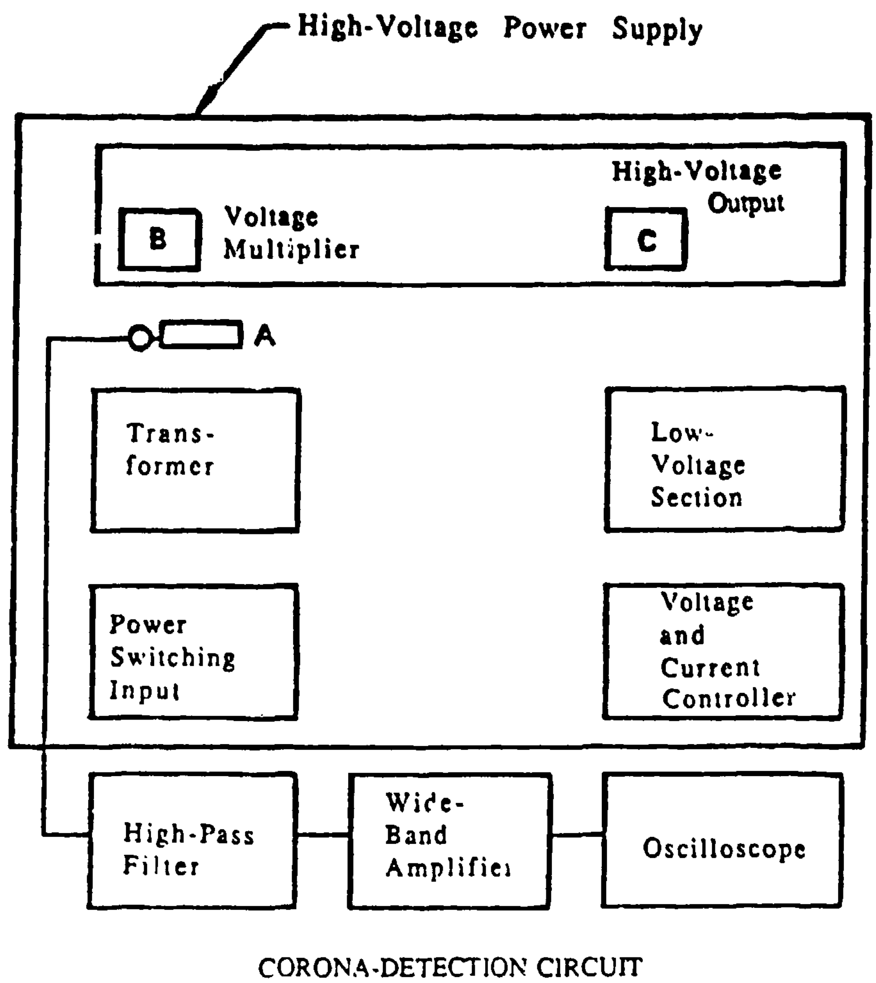

Figure 101. Power Supply Corona Test

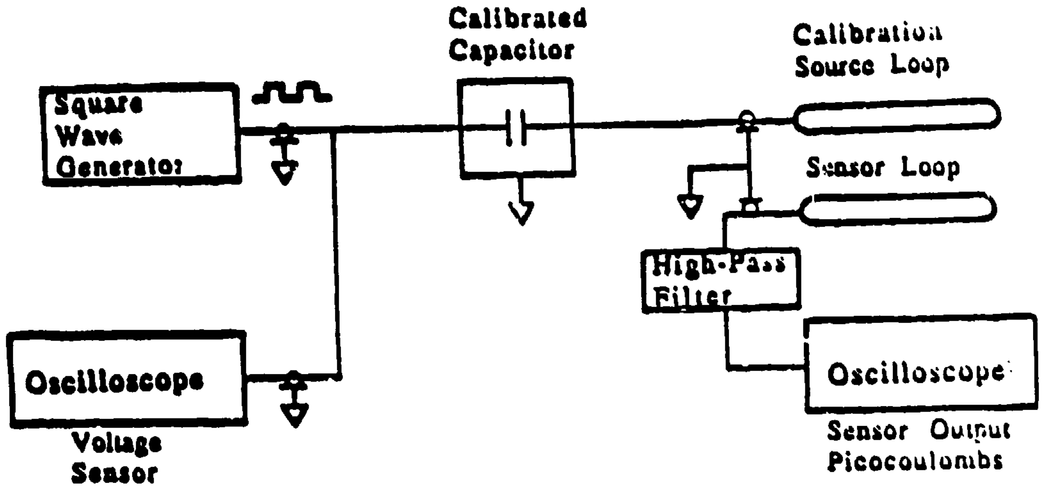

Figure 102. Calibration Equipment

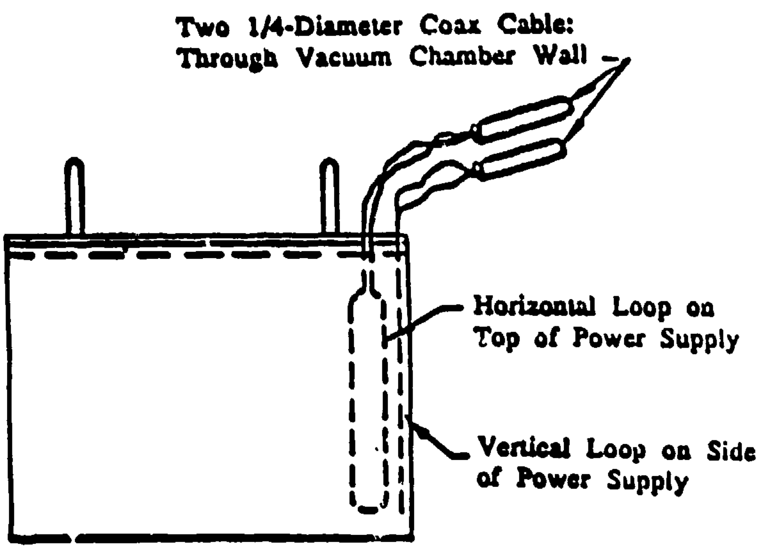

Figure 103. Sensor Attachments

Environmental test chambers can be evaluated with the same corona detection circuits and detectors as are used for airborne parts and circuits. The detectors must be capable of operating at pressure less than 4 x 10^5 N/m^2 (30 Torr). They should respond to frequencies up to 100 MHz, they should be omnidirectional, and they should not contaminate the chamber.

8.6.1 <u>Contamination</u>. The test chambers can be contaminated by foreign gases, dust particles, oxides, salts, and out-gassing products. Helium, argon, and neon effectively reduce the partial discharge initiation voltage. Test chambers should be purged to eliminate contaminating gases unless of course the tested unit generates or releases such gases. Helium and hydrogen will leak through ceramic and glass seals of pressurized units.

Dust particles can intensify local dielectric stress, develop tracking, and eventually form a point electrode. Oxides and salts deposited by handling during assembly, storage, transportation, or operation will degrade insulation materials. They also alter the surface composition of the electrodes.

8.7 <u>Accelerated Life Tests</u>. Accelerated life tests can be conducted using three basic parameters: frequency, temperature, and voltage. Life varies inversely with frequency. That is by doubling the frequency the life is shortened 50 percent or

$$L = \frac{f_o}{f_t}$$

where L is life, f_o is the operating frequency and f_t is the test frequency. Eight to 12 percent overvoltage will shorten insulation life about one order of magnitude from the normal value (Figure 28). However, in accelerated life tests the insulation must operate free of partial discharges at both normal and over-voltage levels. Likewise, insulation can be given an accelerated life test by increasing the test temperature 8^o to 12^oC for each magnitude life decrease. The accelerated life temperature must not exceed the insulation ultimate temperature limit.

Experience has shown that incorporating the following elements into a life test contributes to the development of valid test data.

a. Partial discharge detection readout should be monitored continuously by electronic means.

b. Temperature cycling is required to produce the thermo-mechanical stresses that may enhance partial discharge formation. The temperature should be cycled from minimum to maximum extremes specified for the equipment at least five times. Each cycle should include "soak" time at each temperature extreme to permit the internal components to thermally stabilize. These tests may be performed in either air or vacuum.

c. If partial discharges become more frequent with increasing temperature more temperature cycles should be performed to determine whether the partial discharges increased because of temperature or time.

d. The gas pressure should be kept within the operating range of the tested equipment but at a point corresponding to the closest approach to the Paschen law minimum or highest operating altitude pressure.

e. After completion of the temperature cycling, the high voltage should be turned off and on five times at 5 minute intervals. The off time should be less than 15 seconds. During the power turn-on the partial discharge detectors should be operating and their output should be recorded. An increase in the magnitude and/or quantity of impulses for each on-off cycle indicates that insulation is deteriorating and should be replaced.

f. Life testing should follow the temperature cycling, and should continue for at least 25 percent of the expected life of the equipment.

SECTION IX
MAINTENANCE AND REPAIR

Multitudes of electronic assemblies and subassemblies are destroyed through condemnation or damage during repair and maintenance due to unavailability of parts or subassemblies. Furthermore, it is often very difficult or impossible to determine by test or destructive failure analysis the cause of the failure; that is, thermal overload, overvoltage, or short circuit. This section discusses maintenance, repairability, and failure analysis problems associated with airplane power supplies. Additional subjects include techniques to simplify these all-important costly repairs and reduce the number of throwaway units.

9.1 Maintenance. The three important levels of maintenance are:

Level 1: remove/replace LRU
Level 2: line replaceable unit (LRU) repair
Level 3: shop replaceable unit (SRU) repair

where a radar is an LRU, the power supply is an SRU; and a transformer, solid-state device, or voltage multiplier is a part or submodule of a SRU. Air bases perform Level 1 and some Level 2 maintenance, and air logistic centers (ALC) performs Level 2 and Level 3 maintenance.

Replacement of an LRU is indicated by the flight officer or maintenance officer in charge and the whole unit is replaced. At this time, the problem is not isolated to an SRU or module. When the system is tested by a skilled technician using an approved test set, the faulty module can be isolated, removed, and repaired or destroyed. In some cases there may be a direct short or problem in a connected load, and the power supply may appear defective. Actually, a new power supply, if replaced, would fail in the defective system. Skilled technical personnel can recognize those failure modes and isolate the faulty unit. Inexperienced technical personnel may replace and fail one or two supplies in the process of finding the faulted unit. Inexperience is not the only reason for replacing and faulting good power supplies. For the

technician to do a good job, the test set must have sufficient sensors and test points to accurately determine the system malfunction. Poor test sets and instrumentation often account for power supplies with higher than normal failure rates.

When the system project office (SPO) orders new equipment and test sets, the maintenance and repair group must be part of the review team for the test equipment because they must understand the circuit and test procedures. If ALC personnel are not involved at the beginning of the program there will be a severe loss of time, higher than normal equipment test failures, and test modification time required to get the maintenance shop in operating condition. All equipment maintenance personnel must know the detailed design characteristics to be certain all tests can be accomplished at the air bases and ALCs.

9.2 Test sets. Tests sets sometimes have problems when initially installed at an air base or ALC. It is general industry practice for the system designer to design and manufacture the electronics, then subcontract the test set to another manufacturer or organization within the manufacturing plant.

9.2.1 Problem areas. Several problem areas follow:

- When subcontracted, the test set designer often does not have complete design knowledge of the electronics designs for the test article
- The electronics designer uses different test sensors and techniques than the test set designer to indicate faulted parts and modules.
- The test sets cannot evaluate workmanship or quality control errors in circuits or packaging.
- Few test sets have good EMI or corona detection capability to determine power supply or electronics longevity.
- Test sets require a great amount of debugging during the initial year of operation. This leads to high failure rate of good SRUs during the debugging period.

- Computerized systems require a great amount of practical experience to do a good test analysis. The test operator must be well informed about the test set and test article characteristics to perform a good job.
- Test sets are built to test specified SRU tolerance. When electronic cards are modified with updated parts (with the same nomenclature) and workmanship, some test sets parameters may require modification.
- Test set power supplies give a lot of trouble. Some are very noisy, resulting in instrumentation interference. Some put out spikes that can foil some sensitive feedback and control circuits in the test article.
- Some of the very old simple test sets are preferred to the new units because the tolerances can be adjusted by the operator for better analysis.
- Test equipment is often incompatible with LRU and SRU test requirements because the test equipment is designed and built by test equipment manufacturers not the LRU or SRU manufacturer.
- Self-test SRUs are incompatible with the test sets. Often the test sets have more problems than the units to be tested.

9.2.2. Recommendations. One recommendation is to place a warranty on the electronics and test sets to meet a minimum operational reliability. If not met, the manufacturer would be required to replace the test set with modifications and complete operating instructions for the test set. Also data points and instrumentation should be added so the operator can isolate the fault to a discrete module or part, schedule and price should have lower priority than good quality operational test equipment.

9.3 Pilots and Crewmen. A modern airplane is an electronic machine that requires the service of skilled operators (pilots) and technicians (crewmen) to effectively keep the machine operating. This implies that the pilot must be an observant, skilled electronics engineer. Unfortunately, the pilot must devote full attention to the mission. When electronics fail he only has time to switch,

override, or delete: not repair. The ground base crewmen replace, repair, or send the LRUs to the ALC for repair.

Pilots operate the equipment to the b... of their ability and provide good information, when available, about the failure modes. Flight crewmembers must update and keep current their installation and maintenance procedures to prevent the appearance of unnecessary failure modes. Crewman report the following problems:

- Very old equipment, with more than 15 years service, have high failure rates because of age and environmental fatigue.
- Crewmen who replace a problem with a substitute solution often cause more problems and higher failure rates. All suggested solutions should be thoroughly analyzed and tested before approval is authorized.
- Aircrews have a tendency to replace some cards using trial and error which gives a high failure rate to some good cards.
- In some cases, aircrews have inadequate test equipment to analyze units for card test and replacement. The tendency is to replace a card one or two times before trying the next card in the malfunctioning unit.
- Some good operational LRUs are sent to the repair depot because of poor test equipment and procedures at the air base.
- Airmen and crews must provide better instrumentation and failure analysis reports to make repairs and maintenance more efficient.

9.4 Air Logistic Centers. ALC personnel are skilled and do an excellent job of test, analysis, and repair and have reported many failures; sources of failure; and, in many cases, remedies for failures found in marginal equipment. However, their job is not to redesign, but to maintain and repair and promplty return electronic equipment to its original status. When parts and manufactured modules are available and on schedule, the ALC personnel have accomplished their job successfully. Some ALC repair shop findings follow.

9.4.1. General Problems. The U.S. Air Force specifications cover the system very well as it was developed by the prime manufacturer. The problem with power supplies is that they are designed and developed by a subcontractor for a subcontractor. This deletes the U.S. Air Force from design review control. Thus, the power supply manufacturer only has to design to input-output characteristics; not to full military specification requirements.

- In the future failure rates can be expected to increase, not decrease, because of higher power density packaging, and automation that measures input-output, not characteristics.
- Throwaway units can be justified if they are cost effective and do not have built-in failure modes.
- Manufactures should be allowed to make minimum modifications to improve life, but power supplies must be qualified to meet all the environmental and flight screen tests: NO WAIVER ALLOWED. Some problem areas are:
  a) Power supplies often overheat because of poor cooling, such as power transistors without heat sinks, insufficient coolant, and cooling paths barred by thermal and electrical insulation.
  b) Some waivers have been accepted to pass some environmental specifications such as the -55°C temperature parameter. Those waivers often result in marginal designs with high failure rates.
- Manufacturers should not be allowed to remedy failure modes by "patching" suspect parts or circuits. More thorough analysis should be completed with respect to the input and load characteristics before redesign development.
- Second-source suppliers many times have wrong form and fit with the same part number. In one instance, round units from the first source were replaced by square units from the second source. The second source units had to be stored unused.
- Identical part numbers should only be used for identical parts. Modified units should have new part numbers or dash numbers denoting the modification.

- Some suppliers use cheaper parts to be competitive. This leads to higher failure rates. In one case capacitors with a lower voltage rating than originally specified were used and caused high failure rates.
- Overheating is the greatest failure mode. Integrated circuits fail because of poor hear transfer through silicones and other encapsulants.
- Some power supplies overheat so rapidly it is necessary for the pilot to override the thermal overload relay to perform his mission requirements. This type of operation causes failure.
- Many power supplies are potted with materials that have good properties from -40^{o} to 85^{o}C; but have short life when subjected to the higher or lower temperatures, that is above 85^{o}C and below -40^{o}C.
- A high failure rate has been caused by water condensation on low voltage connectors. Weatherproof connectors should be required on all sealed units. Aircooled units have high failure rates due to condensation.
- Foreign copper has more impurities and leads to higher failure rates. This is noticed mostly in vacuum tube parts, transformers, and general wiring.
- Odd forms and shapes often make repair very difficult. Compact designs many times are impossible to repair without completely replacing a large number of components.
- Repair of potted units often results in poor bonding due to uncleanliness and incompatibility of new and old materials.
- Proprietary circuits and items without U.S. Air Force use approval or QPL designations should be disallowed. All circuits should have schematics.
- Modularized units are easily repaired. Parts are standardized and easy to replace.
- Workmanship appears to be fairly consistent for many power supplies. For higher voltage units, workmanship and packaging defects produce high failure rates.

- Cleaning materials should be specified for all potted or fluid-filled supplies to detect material incompatibility.
- Low voltage boards should not be encapsulated. This makes repairability and maintainability much simpler.
- Some aircooled units get inadequate air cooling at altitude, overheat, and fail.
- Air flowpaths are often eliminated by modifications and redesign.
- Reliability has deviated 30 percent to 40 percent since 1960.
- Some power supplies built in the 1960s are still in demand. Very old units show corrosion. Repair of these units takes a very long time because of the inadequate supply of solid-state devices and long delivery times for replacement parts.
- Some power supplies and aircraft are being phased out over a period of years. For these power supplies, parts are very difficult to obtain. The ALCs have been doing an excellent job of modifying, substituting parts and circuits, and developing good replacements. Many are without updated schematics.

9.4.2 Materials and Processes. A few materials and process problems prevail at the ALCs. Potted power supplies have a lot of trouble with cracking and debonding. Causes for the problem areas are as follows:

- Insufficient cure time for potting materials causes poor bonding and cracking
- Primers are not applied to silicone-insulated modules. Voids and gaps appear between terminals across the part's body.
- Lack of cleanliness causes short circuits through low-resistance debris in the encapsulant
- Materials incompatibility due to cleaning or immersing in operating liquids causes insulations to swell, harden, or crack. All lead to failures and short life. In one case, protective sleeving was placed over high voltage wire and the unit was immersed in FC-77. The wire became swollen, the sleeving cracked, and the unit failed.
- Printed circuit boards do not have conformal coatings.

- Fluorocarbon products such as FC-77 evaporate without leak identification. In leaky units, sludge has been caused by arcing within the unit.
- Silicone wire in silicone-oil-filled units becomes spongy and fails.
- An "air pocket" above the oil allows the air bubble to move about during the flight plan, uncovering some high voltage parts, and resulting in arcs and corona.
- Liquid-filled units often use standard military specification type solder joints with high field stress points within the circuit.
- Liquid-filled modules have insufficient fluid fill. Cleanliness is often neglected.
- Instruction should be given for use of FC-77 and compatibility and leakage problems.

9.4.3. Parts. Parts problems are listed as follows:

- Test screening should be mandatory to eliminate marginal parts.
- All parts should be screened to meet a minimum specification.
- Some capacitors and resistors values charge with age. This throws the system out of tolerance.
- Crushed or broken parts due to insufficient stress relief; solder pull and broken leads are also detected.
- QPL parts are not all identical in characteristics or shape.
- Tantalum capacitors are overstressed when wave soldered.
- Capacitor circuits with tantalum-silver capacitors that were replaced with tantalum-tantalum capacitors have much improved MTBF.
- Parts stored for long periods of time become corroded before being installed in a power supply.

Solid-State devices: Many companies change from "old style" parts to "new" parts without notifying the U. S. Air Force of the changes. Some newer devices are much faster and do not meet the circuit characteristic requirements. This causes many failures.

- Solid-state manufacturers often change device characteristics without changing the device nomenclature. This can cause failure rates to increase.
- Some devices have become obsolete and replaceable units are difficult to impossible to find in time to keep up with high failure-rate electronics.
- Diodes with low voltage drop would help the cooling problem.
- Diodes should not be placed beside power resistors.
- Matched set solid-state devices must be replaced as a set. The replacement matched set devices often are not properly characterized and matched.
- Some solid-state devices appear to have characteristic changes with aging. These changes were severe enough to cause a failure in that device and in other devices in the board.

9.5 Design Problems Recommendations. It is recommended that many high failure rate power supplies can be greatly improved by simple modifications. Some of those modifications follow:

- Some second-source power supplies have the voltages reversed and cannot be used. Better drawing reviews and quality control is recommended.
- Many parts have improper or no heat sinks and overheat. The solution to this design problem is obvious.
- Power supplies should not be used as "fuses" if they are properly specified to have short circuit detection and protection.
- A board mounted next to a high-temperature transformer is poor design and causes the solid-state devices to overheat. Better packaging procedures are required.
- Board flexing during vibration causes solder and trace breakage. More support should be given the boards.
- Second-source units are difficult to repair. The ALC has drawings for first-source units, which are not always identical to the second-source units. Better drawing uniformity is required.

- Qualification units are often built by engineers and skilled technicians. Some failure modes often introduced by the production program do not appear on the drawings.
- Ceramic capacitor coatings often crack and fail the capacitor because of insufficient testing before application.
- Some low voltage cards have no schematics. All that is indicated on the power supply schematic is a board, which was subcontracted to a lower level manufacturer.
- High voltage circuits are usually designated as throwaway units and are not repaired.
- Wire routing in many power supplies is very poor and inconsistent. Some wires are "laid out" so that they cause high failure rates. A high voltage wire should not be allowed to intermittently touch the ground plane during vibration.
- Ties often have loose ends "sparking" to ground planes, causing noise.
- Wires are often too short or too long. The short ones have high breakage and the long ones are doubled back in such a way it makes repair and maintenance difficult.
- Vibration makes wires break at potted joints or connections if not properly laced to a support.
- Epoxy-coated cards replaced during manufacture are often repaired by burning off the epoxy with a hot iron. If the residues are not removed, they cause high failure rates for modified boards.

SECTION X

CONCLUSIONS

This design guide is intended to be used by designers of compact, high density, high voltage electronic power supplies. Formulas and empirical equations are shown for typical high voltage electrode configurations found in electrical equipment. A designer using these empirical formulas and the field plotting methods shown can locate maximum field stresses within electrical insulation systems. Then, the proper dielectrics can be selected for the development of high-quality long-life power supplies.

Insulation design configurations and test methodology are described. Each design must be configured within the space and weight allocations. For this reason, these configurations are only guidelines. Likewise, tests should be accompanied by detailed test procedures before a high voltage design is recommended for fabrication.

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GLOSSARY OF TERMINOLOGY

Adsorption - The adhesion of gas or liquid molecules to the surfaces of solids or liquids with which they are in contact.

Aging - The change in properties of a material with time under specific conditions.

Alternating Current - Current in which the charge-flow periodically reverses and is represented by: $I = I_0 \cos(2\pi ft+\phi)$ where I is the current, I_0 is the initial amplitude, f the frequency, ϕ the phase angle.

Ambient Temperature - The temperature of the surrounding cooling medium, such as gas or liquid, which comes into contact with the heated parts of the apparatus.

Anode - The electrode through with a direct current enters the liquid, gas, or other discrete part of an electrical circuit; the positively charged pole of an electrochemical cell.

Anti-Oxidant - Substance which prevents or slows down oxidation of material exposed to air.

Arcover Voltage - The minimum voltage required to create an arc between electrodes separated by a gas or liquid insulation under specified conditions.

Arc Resistance - The time required for an arc to establish a conductive path in a material.

Askarel - Non flammable synthetic liquid dielectric.

Bond Strength - The measure of adhesion between bonded surfaces.

Breakdown (Puncture) - A disruptive discharge through insulation.

Breakdown Voltage - The voltage at which the insulation between two conductors fail.

Capacitance (Capacity) - That property of a system of conductors and dielectrics which permits the storage of electricity when potential difference exists between the conductors. Its value is expressed as the ratio of quantity of electric charge to a potential difference. A capacitance value is always positive. The charge which must be communicated to a body to raise its potential one unit, represented by C=Q/V, where C is the capacitance, Q the quantity of charge, and V the potential. In a parallel plate condenser

$$C = \frac{KA}{d}$$

where A is the area of the plates, d the distance between them, and K the dielectric constant of the medium.

Capacitor (Condenser) - A device, the primary purpose of which is to introduce capacitance into an electric circuit.

Cathode - The electrode through which an electric current leaves a liquid, gas, or other discrete part of an electric circuit; the negatively charged pole of an electrochemical cell.

Cavity - Depression in a mold.

Cell - A single unit capable of serving as a d-c voltage source by means of transfer of ions in the course of a chemical reaction.

Charge - In electrostatics, the amount of electricity present upon any substance which has accumulated electric energy.

Conductance - The reciprocal of resistance. It is the ratio of current passing through a material to the potential difference at its ends.

Conductivity - Reciprocal of volume resistivity. Conductance of a unit cube of any material.

Conductor - An electrical path which offers comparatively little resistance. A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

Contaminant - An impurity or foreign substance present in a material which affects one or more properties of the material.

Corona - A luminous discharge due to ionization of the gas surrounding a conductor around which exists a voltage gradient exceeding a certain critical value. A type of discharge--sometimes visible--in the dielectric of an insulation system caused by an electric field and characterized by the rapid development of an ionized channel which does not completely bridge the electrode. May be continuous or intermittent. Not a material property, but related to the system, including electrodes.

Corona resistance - The time that insulation will withstand a specified level field-intensified ionization that does not result in the immediate complete breakdown of the insulation.

Corrosion - Chemical action which causes destruction of the surface of a metal by oxidation or chemical combination.

Coulomb - Unit quantity of electric charge; i.e., the quantity transferred by one ampere in one second.

Creep - The dimensional change with time of a material under load.

Creepage (electrical) - Electrical leakage on a solid dielectric surface.

Creepage surface on path - An insulating surface which provides physical separation as a form of insulation between two electrical conductors of different potential.

Critical Voltage (of gas) - The voltage at which a gas ionizes and corona occurs, preliminary to dielectric breakdown of the gas.

Delamination - The separation of layers in a laminate through failure of the adhesive.

Dielectric - (1) Any insulating medium which intervenes between two conductors and permits electrostatic attraction and repulsion to take place across it. (2) A material having the property that energy required to establish an electric field is recoverable in whole or in part, as electric energy.

Dielectric Adsorption - That property of an imperfect dielectric whereby there is an accumulation of electric charges within the body of the material when it is placed in an electric field.

Dielectric Constant (permittivity or specific inductive capacity) - That property of a dielectric which determines the electrostatic energy stored per unit volume for unit potential gradient. The dielectric constant of a medium is defined by ε in the equation

$$F = \frac{QQ'}{4\pi\varepsilon r^2}$$

where F is the force of attraction between two charges Q and Q' separated by a distance r in a uniform medium.

Dielectric Loss - The time rate at which electric energy is transformed into heat in a dielectric when it is subjected to a changing electric field.

Dielectric Loss Angle (dielectric phase difference) - The difference between ninety degrees (90°) and the dielectric phase angle.

Dielectric Loss Factor (dielectric loss index) - The product of its dielectric constant and the tangent of its dielectric loss angle.

Dielectric Phase Angle - The angular difference in phase between the sinusoidal alternating potential difference applied to a dielectric and the component of the resulting alternating current having the same period as the potential difference.

Dielectric Power Factor - The cosine of the dielectric phase angle (or sine of the dielectric loss angle).

Dielectric Strength - The voltage which an insulating material can withstand before breakdown occurs, usually expressed as a voltage gradient (such as volts per mil).

Dielectric Test - Tests which consist of the application of a voltage higher than the rated voltage for a specified time for the purpose of determining the adequacy against breakdown of insulating materials and spacings under normal conditions.

Dispersion - Finely divided particles in suspension in another substance.

Displacement Current - A current which exists in addition to ordinary conduction current in a-c circuits. It is proportional to the rate of change of the electric field.

Disruptive Discharge - The sudden and large increase in current through an insulation medium due to the complete failure of the medium under the electrostatic stress.

Dissipation Factor (loss tangent, tan δ approx. power factor) - The tangent of the loss angle of the insulating material.

Electric Field Intensity - The force exerted on a unit charge. The field intensity E is measured by

$$E = \frac{Q}{4\pi\varepsilon r^2}$$

where r is the distance from the charge Q in a medium having a dielectric constant ε.

Electric Strength (dielectric strength) (disruptive gradient) - The maximum potential gradient that the material can withstand without rupture. The value obtained for the electric strength will depend on the thickness of the material, and on the method and conditions of test.

Electrode - A conductor, not necessarily metal, through which a current enters or leaves an electrolytic cell, arc, furnace, vacuum tube, gaseous discharge tube, or any conductor of the non-metallic class.

Electromagnetic Field - A rapidly moving electric field and its associated moving magnetic field, located at right angles both to the electric lines of force and to their direction of motion.

Electron - That portion of an atom which circles around the center, or nucleus. An electron possesses a negative electric charge, and is the smallest negative charge known.

Encapsulating - Enclosing an article in a closed envelope of plastic.

Energy of a Charge - $W = 1/2\ QV$, given in ergs when the charge Q and the potential V are in electrostatic units.

Energy of the Electric Field - Represented by $W = KE^2$ where E is the electric field intensity in electrostatic units, K the specific inductive capacity, and the energy of the field E in ergs per cm^3.

Epoxy Resins - Straight-chain thermoplastics and thermosetting resins based on ethylene oxide, its derivatives or homologs.

Farad - Unit of capacitance. The capacitance of a capacitor which, when charged with one coulomb, gives a difference in potential of one volt.

Fiber - A thread or threadlike structure such as comprises cellulose, wool, silk, or glass yarn.

Fibre - A specific form of chemically gelled fibrous materials fabricated into sheets, rods, tubes, and the like.

Filler - A substance, often inert, added to a plastic to improve properties and/or decrease cost.

Flame Resistance - Ability of the material to extinguish flame once the source of heat is removed.

Flammability - Measure of the material's ability to support combustion.

Flashover - A disruptive discharge around or over the surface of a solid or liquid insulator

Frequency - The number of complete cycles or vibrations per unit of time.

Graded Insulation - Combination insulations with the portions thereof arranged in such a manner as to improve the distribution of the electric field to which the insulation combination is subjected.

Gradient - Rate of increase or decrease of a variable parameter.

Grounded Parts - Parts which are so connected that, when the installation is complete, they are substantially at the same potential as the earth.

Ground Insulation - The major insulation used between a winding and the magnetic core or other structural parts, usually at ground potential.

Hall Effect - The development of potential difference between the two edges of a strip metal in which an electric current is flowing longitudinally, when the plane of the strip is perpendicular to a magnetic field.

Hardener - A substance or mixture of substances added to plastic composition, or an adhesive to promote or control curing.

Heat Sink - Any device that absorbs and stores energy from a hot object.

Hertz (Hz) - A term replacing cycles-per-second as a unit of frequency.

Hygroscopic - Tending to absorb moisture.

Hysteresis - An effect in which the magnitude of a resulting quantity is different during increases in the magnitude than during decreases. It is caused by internal friction and is accompanied by the production of heat within the substance. Electric hysteresis occurs when a dielectric material is subjected to a varying electric field as in a capacitor in an alternating - current circuit.

Impedance - The total opposition that a circuit offers to the flow of alternating current or any other time varying current at a particular frequency. It is a combination of resistance R and reactance X, measured in ohms, and designated by Z.

$$Z = (R^2 + X^2)^{1/2}.$$

Impregnate - To fill the voids and interstices of a material with a compound.

Impulse - A unidirectional surge generated by the release of electric energy into an impedance network.

Impulse Ratio - The ratio of the flashover, sparkover, or breakdown voltage of an impulse to the crest value of the power-frequency flashover, sparkover, or breakdown voltage.

Insulation - Material having a high resistance to the flow of electric current to prevent leakage of current from a conductor.

Insulation Resistance - The ratio of the applied voltage to the total current between two electrodes in contact with a specific insulator.

Insulation System - All of the insulation materials used to insulate a particular electrical or electronic product.

Insulator - A material of such low electrical conductivity that the flow of current through it can usually be neglected.

Interstice - A minute space between one thing and another, especially between things closely set or between the parts of a body.

Ion - An electrified portion of matter of sub-atomic, atomic, or molecular dimensions such as is formed when a molecule of gas loses an electron (when the gas is stressed electrically beyond the critical voltage) or when a neutral atom or group of atoms in a fluid loses or gains one or more electrons.

Ion Exchange Resins - Small granular or bead-like particles containing acidic or basic groups, which will trade ions with salts in solutions.

Ionization - Generally, the dissociation of an atom or molecule into positive or negative ions or electrons. Restrictively, the state of an insulator whereby it facilitates the passage of current due to the presence of charged particles (usually induced artificially).

Laminated Plastics - Layers of a synthetic resin-impregnated or coated base material bonded together by means of heat and pressure to form a single piece.

Lamination - The process of preparing a laminate. Also any layer in a laminate.

Line of Force - Concept used in the description of an electric or magnetic field to represent the force between charges of magnetic dipoles.

Mat - A randomly distributed felt of glass fibers used in reinforced plastics.

Moisture Resistance - The ability of a material to resist absorbing moisture from the air or when immersed in water.

Nylon - The generic name for synthetic fiber-forming polyamides.

Open Cell - Foamed or cellular material with cells which are generally interconnected. Closed cells refers to cells which are not interconnected.

Organic - Designating or composed of matter originating in plant or animal life or composed of chemicals of hydrocarbon origin, either natural or synthetic.

Oscillatory Surge - A surge which includes both positive and negative polarity values.

Overpotential - A voltage above the normal operating voltage of a device or circuit.

Partial Discharge - A partial discharge is an electric discharge that only partially bridges the insulation between conductors when the voltage stress exceeds a critical value. These partial discharges may, or may not, occur adjacent to a conductor. Partial discharge is often referred to as "corona" but the term "corona" is preferably reserved for localized discharges in cases around a conductor, bare or insulated, remote from any other solid insulation.

Partial Discharge Pulse - A partial discharge pulse is a voltage or current pulse which occurs at some designated location in the test circuit as a result of a partial discharge.

Partial Discharge Pulse Charge - The quantity of charge supplied to the test specimen's terminals from the applied voltage source after a partial discharge

pulse has occurred. The pulse charge is often referred to as the apparent charge or terminal charge. The pulse charge is related but not necessarily equal to the quantity of charge flowing in the localized discharge.

Partial Discharge Pulse Energy - The partial discharge pulse energy is the energy dissipated during one individual partial discharge.

Partial Discharge Pulse Repetition Rate - The partial discharge pulse repetition rate is the number of partial discharge pulses of specified magnitude per unit time.

Partial Discharge Pulse Voltage - The peak value of the voltage pulse which, if inserted in the test circuit at a terminal of the test specimen, would produce a response in the circuit equivalent to that resulting from a partial discharge pulse within the specimen. The pulse voltage is also referred to as the terminal corona pulse voltage.

Permittivity. - Preferred term for dielectric constant.

pH - The measure of the acidity or alkalinity of a substance, neutrality being at pH 7. Acid solutions are under 7; alkaline solutions over 7.

Phenolic Resin - A synthetic resin produced by the condensation of phenol with formaldehyde.

Plastic - High polymeric substances, including both natural and synthetic products, but excluding the rubbers, that are capable of flowing under heat and pressure at one time or another.

Plastic Deformation - Change in dimensions of an object under load that is not recovered when the load is removed.

Plasticizer - Chemical agent added to plastics to make them softer and more flexible.

Polarity - An electrical convention determining the direction in which current tends to flow.

Polyamide - A polymer in which the structural units are linked by amide or thioamide groupings.

Polycarbonate Resins - Polymers derived from the direct reaction between aromatic and aliphatic dihydroxy compounds with phosgene or by the ester exchange reaction with appropriate phosgene derived precursors.

Polyester - A resin formed by the reaction between a dibasic acid and a dihydroxy alcohol.

Polyethylene - A thermoplastic material composed of polymers of ethylene.

Polyisobutylene - The polymerization product of isobutylene, also called butyl rubber.

Polymer - A compound formed by polymerization which results in the chemical union of monomers or the continued reaction between lower molecular weight polymers.

Polymerize - To unite chemically two or more monomers or polymers of the same kind to form a molecule with higher molecular weight.

Polymethyl Methacrylate - A transparent thermoplastic composed of polymers of methyl methacrylate.

Polypropylene - A plastic made by the polymerization of high-purity propylene gas in the presence of an organometallic catalyst at relatively low pressures and temperatures.

Polystyrene - A thermoplastic produced by the polymerization of styrene (vinyl benzene).

Polyvinyl Acetate - A thermoplastic material composed of polymers of vinyl acetate.

Polyvinyl Butyral - A thermoplastic material derived from butyraldehyde.

Polyvinyl Chloride (PVC) - A thermoplastic material composed of polymers of vinyl chloride.

Polyvinyl Chloride Acetate - A thermoplastic material composed of copolymers of vinyl chloride and vinyl acetate.

Polyvinylidene Chloride - A thermoplastic material composed of polymers of vinylidene chloride (1,1-dichloroethylene).

Potential - The work per unit charge required to bring any charge to the point from an infinite distance.

Potting - Similar to encapsulating, except that steps are taken to insure complete penetration of all voids in the object before the resin polymerizes.

Power - The time rate at which work is done; equal to W/t where W is amount of work done in time t. Power will be obtained in watts if W is expressed in joules and t in seconds.

Power Factor - 1) In an alternating current circuit, it is the power indicated by a watt meter, divided by the apparent power, the latter being power measured by a voltmeter and ammeter. 2) It is the multiplier used with the apparent power to determine how much of the supplied power is available for use. 3) That quantity by which the apparent power must be multiplied in order to give the true power. 4) Mathematically, the cosine of the angle of phase difference between current and voltage applied.

Pressure - Force measured per unit area. Absolute pressure is measured with respect to zero pressure. Gauge pressure is measured with respect to atmospheric pressure.

Proton - A sub-atomic positively charged particle.

Pulse - A wave which departs from a first nominal state, attains a second nominal state, and ultimately returns to the first nominal state.

Relative Humidity - Ratio of the quantity of water vapor present in the air to the quantity which would saturate it at any given temperature.

Resin - An organic substance of natural or synthetic origin characterized by being polymeric in structure and predominantly amorphous. Most resins, though not all, are of high molecular weight and consist of long chain or network molecular structure. Usually resins are more soluble in their lower molecular weight forms.

Resistance - Property of a conductor that determines the current produced by a given difference of potential. The ohm is the practical unit of resistance.

Resistivity - The ability of a material to resist passage of electrical current either through its bulk or on a surface. The unit of volume resistivity is the ohm-cm.

Roentgen - The amount of radiation that will produce one electrostatic unit of ions per cubic centimeter volume.

Schering Bridge - An alternating current form of wheatstone bridge used for comparing capacitances or for measuring the phase angle of a capacitor by comparison with a standard.

Semiconductor - A material whose resistivity is between that of insulators and conductors. The resistivity is often changed by light, heat, and electric field, or a magnetic field. Current flow is often achieved by transfer of positive holes as well as by movement of electrons.

Sheet - Thin plannar materials.

Shelf Life -Length of time under specified conditions that a material retains its usability.

Silicone - Polymeric materials in which the recurring chemical group contains silicon and oxygen atoms as links in the main molecular chain.

Solvent - A liquid substance which dissolves other substances.

Sparkover - A disruptive discharge between electrodes of a measuring gap, such as a sphere gap or oil testing gap.

<u>Specific Gravity</u> - The density (mass per unit volume) of any material divided by that of water at standard temperature and pressure.

<u>Staple Fibers</u> - Fibers of spinnable length manufactured directly or by cutting continuous filaments to short lengths.

<u>Storage Life</u> - The period of time during which a liquid resin or adhesive can be stored and remain suitable for use. Also called Shelf Life.

<u>Surface Creepage Voltage</u> - See creepage.

<u>Surface Flashover</u> - See Flashover.

<u>Surface Leakage</u> - The passage of current over the boundary surfaces of an insulator as distinguished from passage through its volume.

<u>Surface Resistivity</u> - The resistance of a material between two opposite sides of a unit square of its surface. Surface resistivity may vary widely with the conditions of measurement.

<u>Surge</u> - A transient variation in the current and/or potential at a point in the circuit.

<u>Tear Strength</u> - Force required to initiate or continue a tear in a material under specified conditions.

<u>Tensile Strength</u> - The pulling stress required to break a given specimen.

<u>Thermal Conductivity</u> - Ability of a material to transport thermal energy.

<u>Thermal Endurance</u> - The time at a selected temperature for an insulating material or system of materials to deteriorate to some predetermined level of electrical, mechanical, or chemical performance under prescribed conditions of test.

<u>Thermal Expansion (Coefficient of)</u> - The fractional change in length (sometimes volume) of a material for a unit change in temperature.

<u>Thermoplastic</u> - A classification of resin that can be readily softened and resoftened by heating.

<u>Tracking</u> - Scintillation of the surface of an insulator, may produce enough heat to leave a degraded track of carbon.

<u>Tracking Resistance</u> - See arc resistance.

<u>Transient</u> - That part of the change in a variable that disappears during transition from one steady-state operating condition to another.

<u>Tubing</u> - Extruded non-supported plastic or elastomer materials.

Urea-Formaldehyde Resin - A synthetic resin formed by the reaction of urea with formaldehyde. An amino resin.

Urethane - A synthetic resin formed by the reaction of a isocyanate resin (nitrogen, carbon, and oxygen radical) with an alcohol.

Vinyl Resin - A synthetic resin formed by the polymerization of compounds containing the group CH2 = CH-.

Viscosity - A measure of the resistance of a fluid to flow (usually through a specific orifice).

Volt - Unit of electromotive force. It is the difference of potential required to make a current of one ampere flow through a resistance of one ohm.

Voltage - The term most often used in place of electromotive force, potential difference, or voltage drop, to designate electric pressure that exists between two points and is capable of producing a flow of current when a closed circuit is connected between the two points.

Volume Resistivity (Specific Insulation Resistance) - The electrical resistance between opposite faces of 1-cm cube of insulating material, commonly expressed in ohm-centimeters. The recommended test is ASTM D257-61.

Vulcanization - A chemical reaction in which the physical properties of an elastomer are changed by reacting it with sulfur or other cross-linking agents.

Water Absorption - Ratio of the weight of water absorbed by a material to the weight of the dry material.

Wire - A metallic conductor of round, square, or rectangular section may be either bare or insulated.

Working Life - The period of time dur' hich a liquid resin or adhesive, after mixing with catalyst, solvent, or other compounding ingredients, remains usable.

Yield Strength - The lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic; above it, elastic-plastic

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